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Technical and Economical Assessment on Tethered Wind Energy Systems (TWES)

A Subcontract Report

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FOREWORD

The Solar Energy Research Institute (SERI), a Division of the Midwest Research Institute, has been authorized by the U.S. Department of Energy to provide technical management for the Advanced/Innovative Wind Energy Concepts (AIWEC) program. The focus of the AIWEC program is to establish the technical potential and feasibility of advanced concepts in wind energy conversion.

This report summarizes the work performed by Tetra Tech, Inc., for SERI under subcontract XE-0-9172-2. Okitsugu Furuya was the project principal investigator, and Richard L. Mitchell was the project technical monitor. The objective of this assessment effort was to establish the potential of tethered wind energy systems for energy conversion in the upper atmosphere. Of the many concepts investigated, the VTOL lift generation concept had the highest potential.

Richard L. Mitchell
Project Technical Monitor

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NOMENCLATURE

C	Component cost ($)
C_D	Drag coefficient
C_L	Lift coefficient
C_P	Power coefficient
C_T	Thrust coefficient
D	Diameter of rotor (m)
	Drag force (N)
f	Frequency (Hz)
I	Transmission current (A)
L	Lift force (N)
L_{tether}	Length of tether (m)
L/D	Ratio of lift force to drag force
P	Power (kw)
P_R	Rated power (kw)
Q	Torque produced by rotor (N-m)
S_{wing}	Wing area (m^2)
S_{shroud}	Area of shroud (m^2)
T_{tether}	Tension of tethering cable (N)
U	Velocity (m/sec)
v	Wind velocity m/sec
V	Transmission voltage (KV)
V_o	Constant used in Weinbull distribution
W_t	Component weight (kg)
α	Constant used in Weinbull distribution
λ	Ratio of rotor tip speed to wind speed, u_t/u_∞
η	Efficiency

Subscripts

max	at maximum
opt	at optimum
t	of tip
R	at rated
∞	of wind

1.0 INTRODUCTION

The wind energy existing at high altitude has been investigated as a potential energy resource by a few foreign countries such as Australia and Austria. The seasonal prevailing wind at an altitude of around 10 km is commonly called a "jet stream", the maximum wind speed of which even reaches 50 meters per second. In terms of the average power density, it can be as high as 16 KW/m^2 at northeastern U.S. sites such as New York, New York*. This can compare with that of the ground level, the maximum value at the U.S. sites of which will be about 0.5 KW/m^2. The average energy density of the upper wind is as much as 30 times that of the ground level.

The objective of the present study is, therefore, to determine whether it is technically feasible to generate electricity in the upper air and transmit it to the ground base with the available state-of-the-art. We will then assess the economy of electricity generated in such a method.

The concept of the Tethered Wind Energy System (TWES) has been studied by two groups of researchers to date. The first group is at the University of Sydney, Australia and the second one is at the Institut für Angewandte Systemtechnik, Austria. In terms of lift-generation methods they have used quite different approaches. Roberts, et. al. (1980) of Australia proposed a wing concept, whereas Riegler (1980) of Austria employed the balloon for lifting the air station to the high altitude. In the former, the lift is entirely generated by the lifting force on the wing, whereas that of the latter system depends on the buoyancy force of the balloon.

One of the most serious problems with the wing concept exists in low-wind and deployment/landing operations when not enough

* The U.S. upper wind data were studied and compiled by O'Doherty and Roberts (1981), particularly for the design of Tethered Wind Energy Systems.

wing lift is generated to support the heavy air platform at such conditions. Roberts (1980) recommended a method of feeding power back to the generators, which would then be used as motors to drive the rotors. However, the air station is tethered to the ground station so that it should circle around until the wind speed recovers that of stalling condition. A similar operation is necessary for deployment and landing of the system. Not only is a large area required for such an operation, but also the control system for the unmanned operation could be very complex and expensive. This type of operational problem never exists for the balloon system. However, it was shown in the Lighter Than Air (LTA) study (1975) that the loss of buoyancy force of the balloon due to the air density decrease would be substantial. With the current state-of-the-art, it seemed impossible to build a large-scale balloon which would generate enough lifting forces to station the air platform at high altitude. Furthermore, the same LTV report indicated a substantially higher cost for design and fabrication of large-scale balloons.

In the present study, we concentrated on searching for alternative lift generation concepts which would resolve the problems mentioned above. Two such methods considered here are the hybrid concept and VTOL concept. The hybrid concept combines the balloon and wing. At the low wind speed conditions, the balloon could carry the weight at a certain low altitude, whereas at regular high altitude operations the wing would provide the entire lift. In this way, the complex operational problems with the wing concept and the problem of the entire loss of buoyancy force with the balloon only, will be eliminated.

The VTOL concept, on the other hand, will take advantage of the simplicity and economy of the wing system except for the low wind speed operations. At such conditions the rotors will be rotated in helicopter-like position to generate the upward lifting forces. This will require no circling manipulation nor need a large size deployment/landing area.

These two concepts were extensively studied in the present study for determining the cost of electricity of the Tethered Wind Energy System.

Another important aspect to be mentioned here is related to the technical and economical assessment methodology for the TWES. In the present study, we have simply depended upon the current state-of-the-art for various mechanical and electrical components. The performance, cost and weight of each component used here were determined by the availability of such components as off-the-shelf products. An effort has been made to use as little new development and technology as possible in order to provide a realistic number for the cost of electricity. It was concluded in our study that the maximum rated power for the TWES potentially built without particularly developing new components would be about 2 MW. The main hurdle in building a larger system exists in the area of high RPM lightweight generators, transformers and solid-state rectifiers. Many such electrical components used here came from the aircraft technology, but the maximum power rating currently available was limited to about 500 kw.

The cost of electricity (COE) determined here is, therefore, for a TWES having the rated power of 500 kw, 1 MW or 2 MW, by assuming four rotors and generators for the 2 MW system. The determining of COE beyond 2 MW will require the development and design of the new components particularly suitable for the TWES environments. With such developmental work done in the future, the COE vs. rated power curve should belong to a different category, i.e., it would become much more competitive even to the COE of fossil fuel in the near future. However, justification for such a speculation should be left to further study, and we will present the COE based on the available state-of-the-art at the time of the investigation.

2.0 HIGH ALTITUDE WIND ENERGY OF THE U.S.

The basic source for generating the jet stream is solar heating on the tropic and the cool Arctic regions combined with the Earth's rotation about its axis. There exist two main jet streams on the Earth; one is the subtropical jet stream, and the other is the polar-front jet stream (or polar jet stream) (see Figure 2.1). The characteristics of these jet streams are similar to each other, but quite different from the general atmospheric circulations such as gradient winds and geostrophic winds. One of the most eminent characteristics is the large seasonal variation in jet stream path, latitude, altitude and mean wind speed. Figure 2.2 shows a variation of the zonal component of mean geostrophic wind in January and July at 80°W of North America. It is also shown in Figure 2.3 that the vector mean wind isotachs at 200 mb vary significantly between winter and summer. For example, at Nashville, Tennessee (N36°, W87°), the monthly mean wind speed exceeds 45 m/sec in January, but reduces to below 15 m/sec in August.

Detailed upper atmospheric wind analysis was made by O'Doherty and Roberts (1981) at SERI. They collected the wind data and statistically analyzed them for 54 sites in the United States. In their analysis it was shown that the city of New York has the highest mean power density of 16.2 kw/m^2 at 300 mb (Figure 2.4). Although higher wind speeds are observed at higher altitudes, the highest mean power density does not take place there but at lower altitudes, at 250 mb ~ 300 mb ($10360^m \sim 9160^m$) due to the change of air density.

O'Doherty and Roberts proved in their report that the standard surface wind energy technique could also be applied to the treatment of the upper wind data. All wind data were then compiled by using an integrated Weibull model, i.e.,

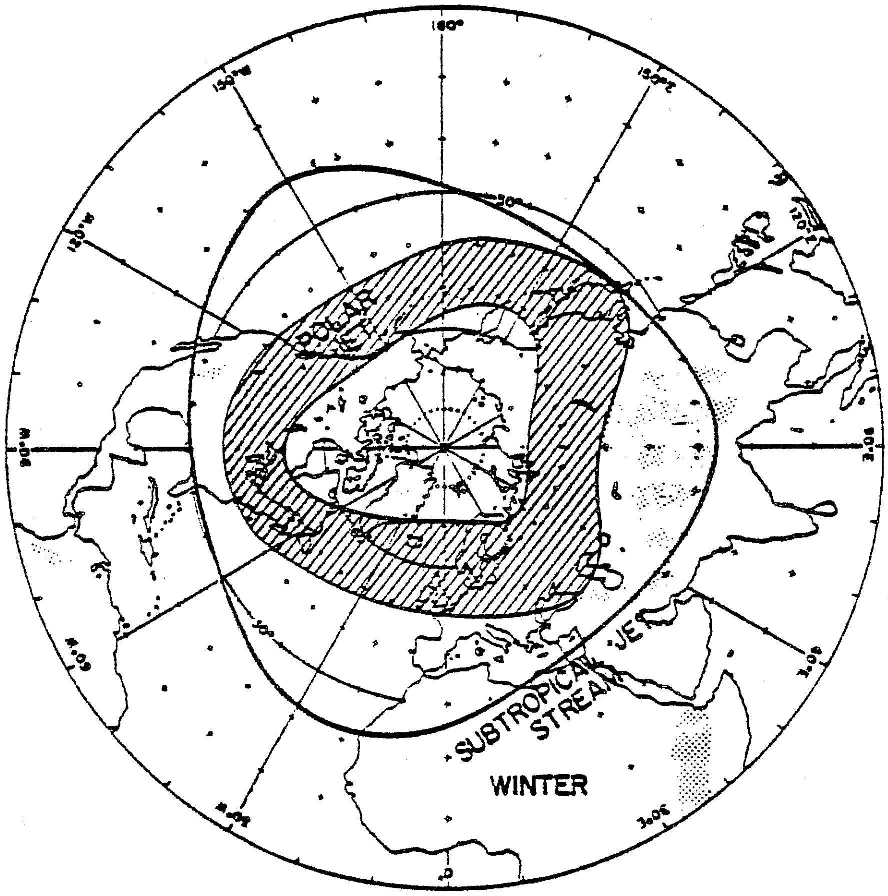


FIGURE 2.1 Mean axis of subtropical jet stream during winter, and area (shaded) of principal activity of polar-front jet stream (after Riehl, 1962)

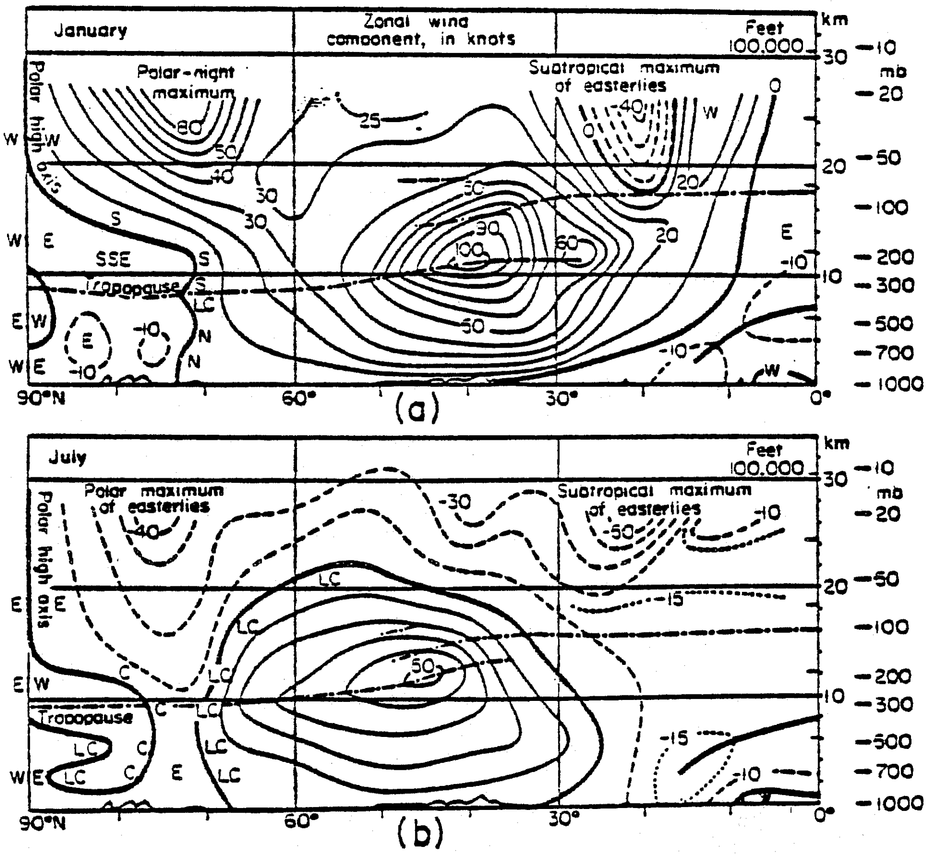
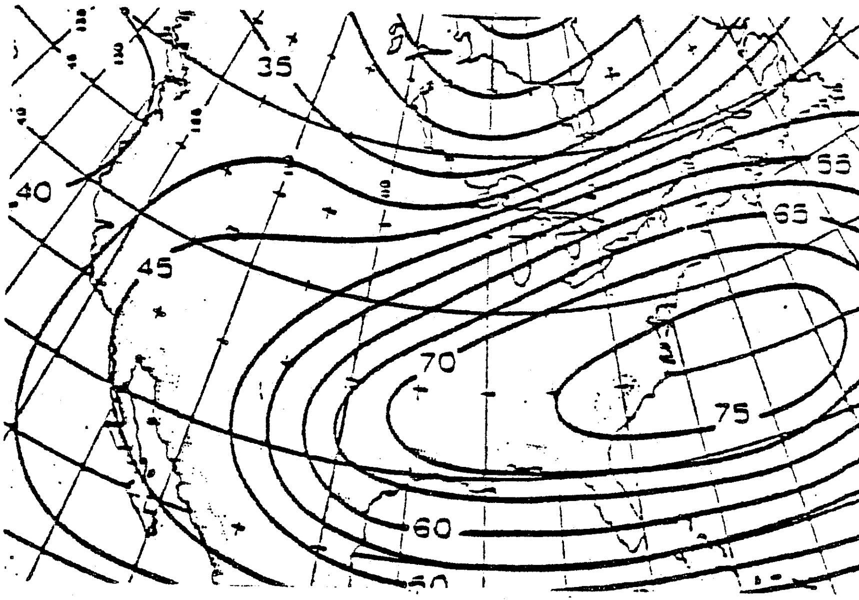
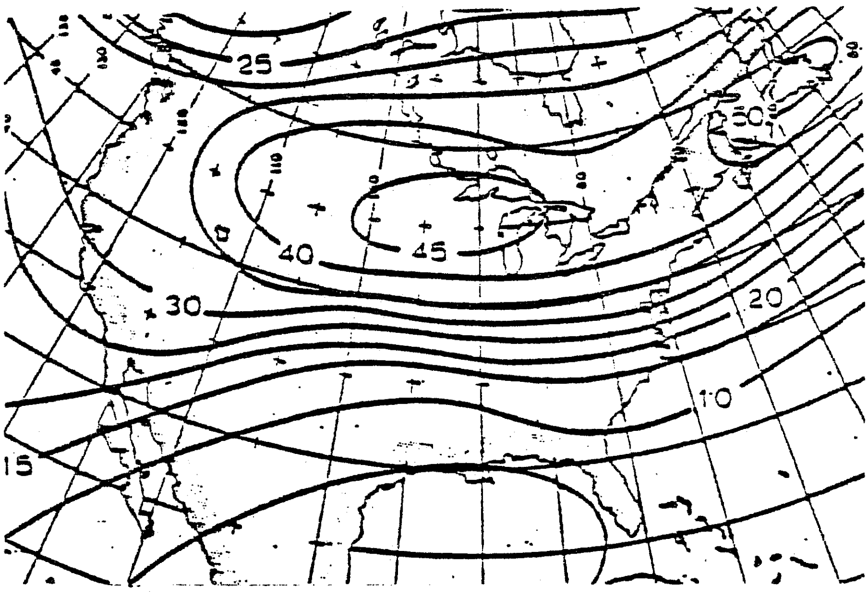


FIGURE 2.2 Zonal component of mean geostrophic wind at 80°W in (a) January and (b) July. Isotachs in knots; dashed for east winds. Dash-dotted lines show mean tropopause heights (after Kochanski, 1955).



(a)



(b)

FIGURE 2.3 Vector mean wind isotachs(knots) at 200 mb in (a) Dec-Jan-Aug and (b) Jun-July-Aug. (after Crutcher and Halligan,1967)

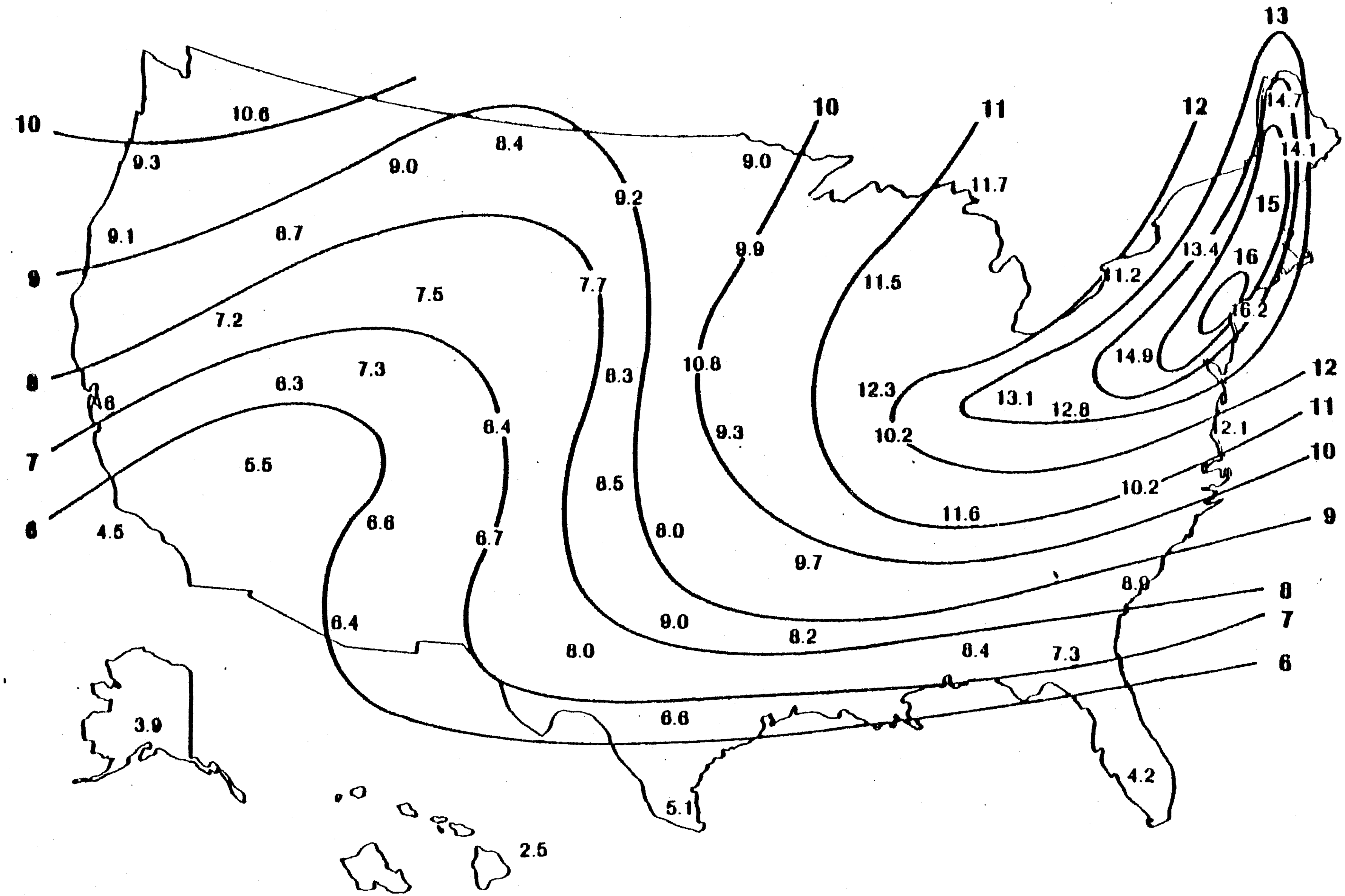


FIGURE 2.4 Isopleths of mean power density at 300 mb kw/m^2 (after O'Doherty and Roberts, 1981)

$$p(V) = \begin{cases} 1 - e^{-(V/V_o)^{\alpha}} & \text{for } V \geq 0 \\ 0 & \text{elsewhere} \end{cases}$$

where V_o and α are the two constants to be determined to provide a good fit for the data. The probability distributions of velocity were then presented on a log-log scale paper called "Weibull paper" at various altitudes. This presentation is quite useful in that the only requirement for the user to utilize these charts will be to determine α and V_o. Figures 2.5(a) and (b) present the characteristic wind duration curves and power duration curves at New York which were constructed at various altitudes based on the statistical graphs presented by O'Doherty and Roberts. It apparently shows that the highest power is available at 300 mb, consistent with the results of O'Doherty and Roberts. These two wind energy curves form the basis for the assessment of the Tethered Wind Energy System and are used throughout the present study.*1

Note *1 The choice of New York was made here in order to provide the largest possible power output and therefore the lowest cost of electricity (COE) in the continent of the United States

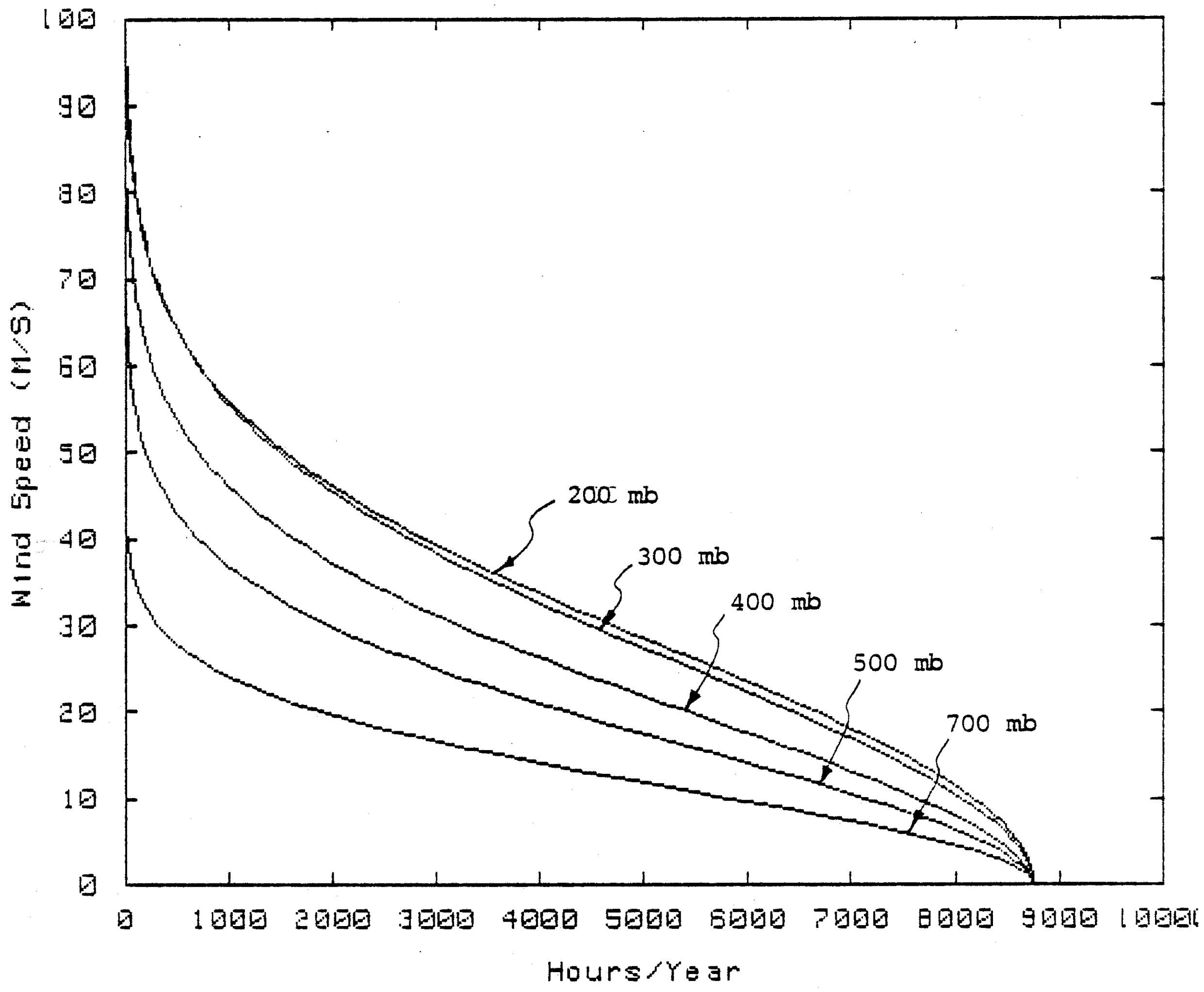


FIGURE 2.5a Wind duration curves for New York, New York at various altitudes
(reconstructed from the data of O'Doherty and Roberts, 1981)

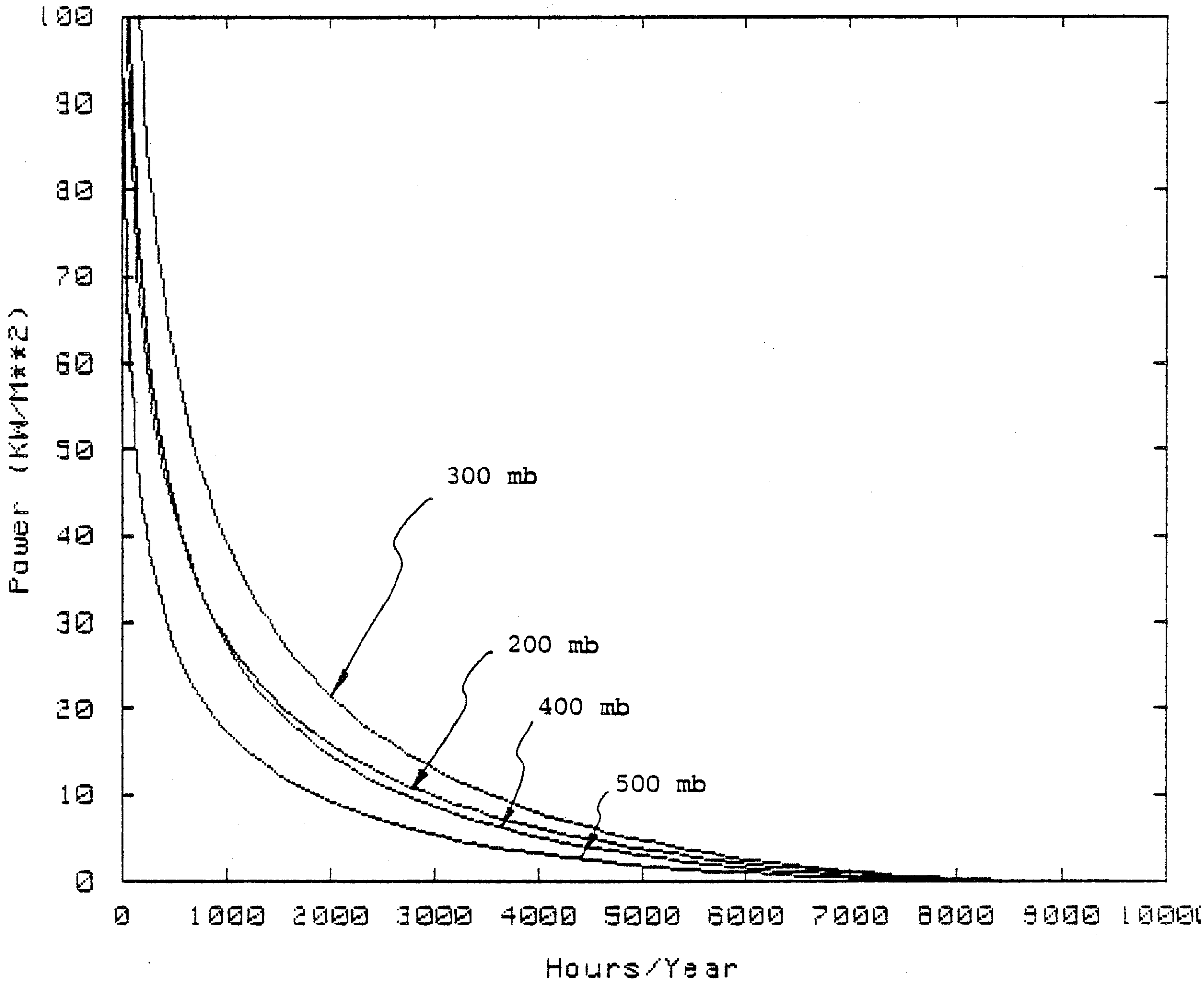


FIGURE 2.5b Power Duration Curve for New York, New York at various altitudes (reconstructed from the data of O'Doherty and Roberts,1981)

3.0 LIFT GENERATION

The lift device for the present use should satisfy the various conditions and requirements specific to the Tethered Wind Energy System. These include:

i) lift at low and high winds,
ii) effect of air density reduction on lift generation mechanism,
iii) deployment and landing methods,
iv) safety,
v) maintenance,
vi) available current technology and
vii) cost.

In what follows we will evaluate four possible lift methods with particular emphasis on the above factors. A qualitative evaluation for these four devices is then presented in Table 3.1.

3.1 WING CONCEPT

The mono-plane type airframe with diffusion augmented turbine configuration has been studied by Fletcher and Roberts (1979) at the University of Sydney (see Figure 3.1(a)). Although this type of wing system can generate enough lifting force at high wind speeds, it fails to do so at low wind speeds or at the time of deployment and landing. As has been mentioned in the previous section, one of the upper wind characteristics is seasonal. Furthermore, even during the high wind season a finite percentage of the low wind period exists. The wind and lift-augmented system cannot be designed to accommodate such a low wind speed and thus will stall. Fletcher and Roberts recommended a method of pumping power back to the generators. They now work as motors to drive wind-rotors which act as propellers to thrust the air station. Since the air station is tethered to the ground station, it should circle or tack about this point

TABLE 3.1

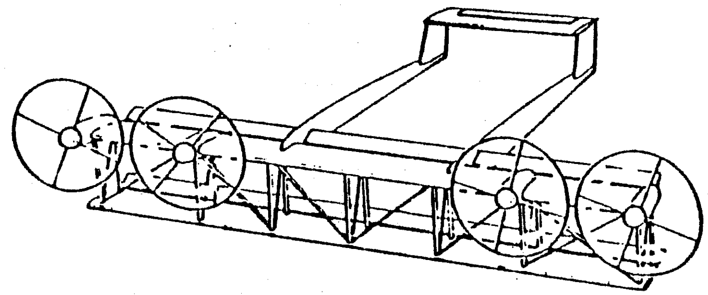
COMPARISON FOR LIFT GENERATION TECHNOLOGY

	Wing	Balloon	Hybrid	VTOL
Lift at low wind	X	O	O	□
Lift at high wind	O	X	O	O
Effect of air density on lift	□	X	□	□
Deployment and landing	X	□	□	O
Safety	X	O	O	□
Maintenance	O	X	X	□
Current technology	O	□	X	O
Cost	O	X	X	□

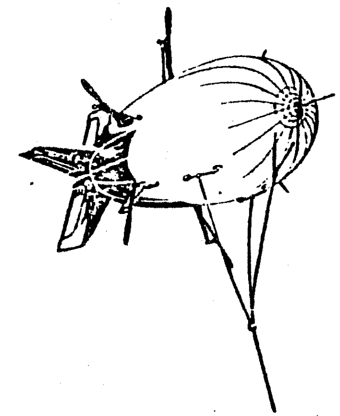
O Excellent

□ Good

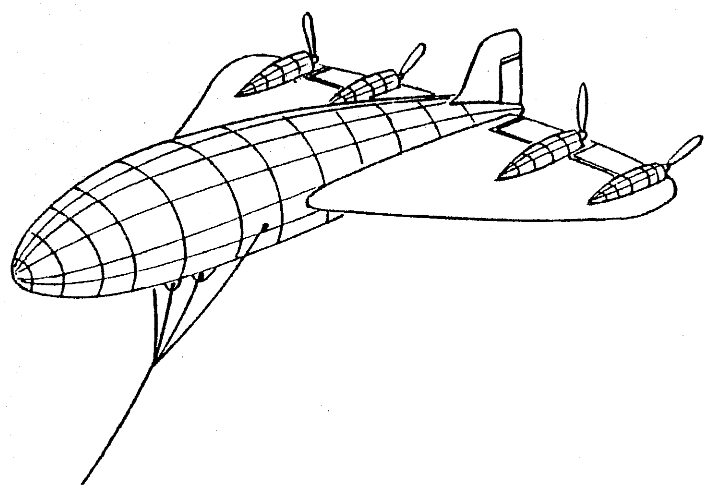
X Poor



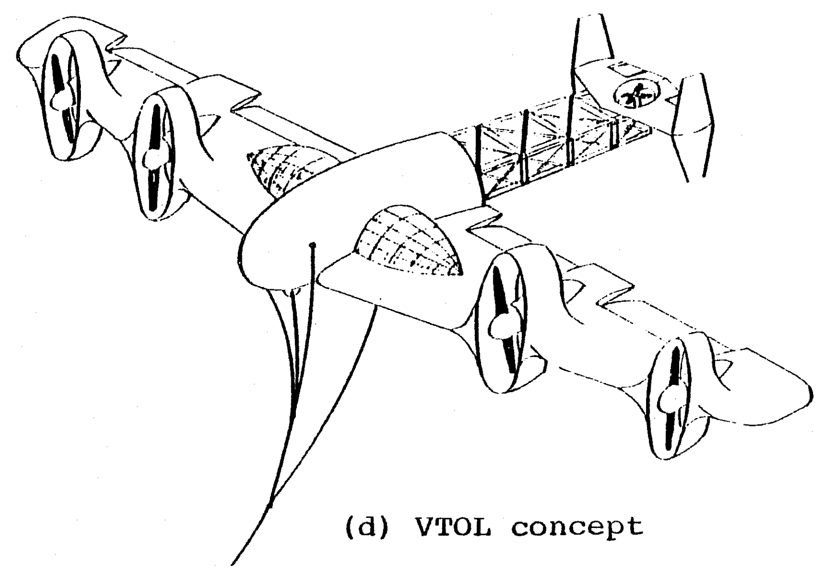
(a) Wing concept (after Roberts and Blacker, 1980)



(b) Balloon concept (after Riedlar, et. al, 1980)



(c) Hybrid concept



(d) VTOL concept

FIGURE 3.1 Various Lift Generation Concepts until the wind speed recovers that beyond the stall speed. A similar operation is required for deployment and landing of the system. Not only is a large area required for such an operation, but also the control system needed for the unmanned landing and take-off could be extremely expensive and require further investigation and development. As far as the cost of wing construction and its technology are concerned, this system has superiority over other candidate systems. However, it must be mentioned that the cost for developing and installing the devices and mechanisms required for the low wind speed operations will outweigh the merit of using the wing system.

3.2 BALLOON CONCEPT

The balloon type platform with open turbine concept has been extensively studied by Riedler, et. al. (1980) of the Institut für Angewandte Systemtechnik, Research Centre, Graz, Austria (see Figure 3.1.(b)). The system has no inherent stall phenomenon even at low wind speeds by employing the static lift due to buoyancy of helium. The air station can stay at a designed altitude even when the wind entirely dies down. The deployment and landing operations of the system do not require any specific devices or methods except that such operations for balloons are tedious under high ground wind environments.

One of the most serious problems of using the balloon for TWES is a severe loss of buoyancy force at high altitude. At 10 km altitude, the atmospheric pressure decreases to one-third of that of sea level. This leads to a limited ceiling to the altitude for the balloon or airship to be possibly used. Figure 3.2 clearly shows such limitation for a helium-filled airship; the net lifting force of the airship becomes negative at an altitude of around 9 km. This graph was constructed based on the data from the Proceedings of the Lighter Than Air (LTA) technology, edited by Vittek (1975), sponsored by the U.S. Navy. The data obtained there are now considered to be

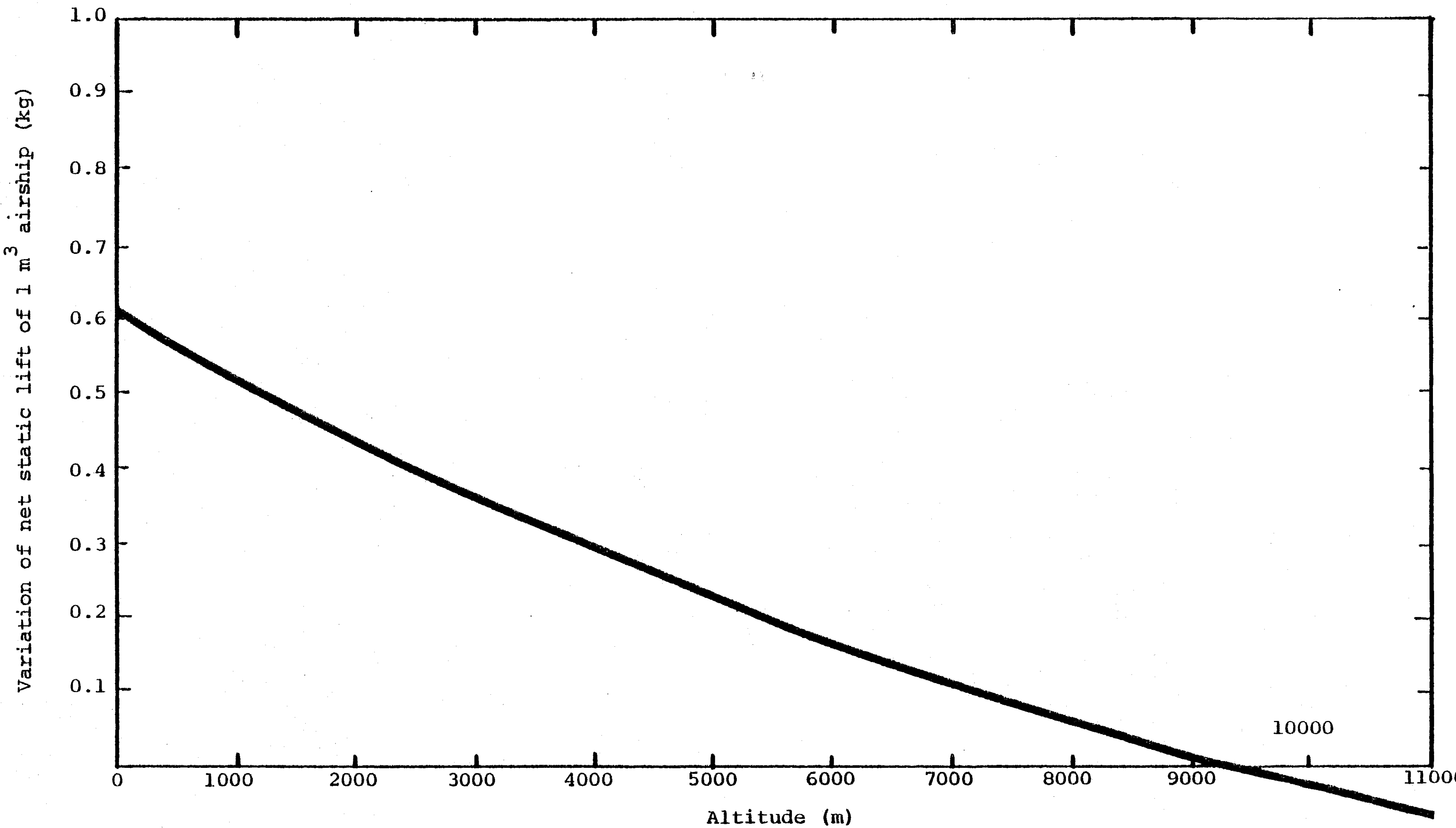


FIGURE 3.2 Available static lift of airship (1 m^3) vs. altitude (constructed from the data of the Proceedings, Vittek, editor (1975))

the latest regarding airship technology. It could, of course, be possible to construct the airship much lighter than that quoted in this Proceedings, but it would require a substantial study and developmental work before its achievement.

As far as the balloon technology is concerned, not much progress has been made since the era of the airship in the 1930's. The balloon skeleton construction is quite complex. Due to the large drag force acting on the balloon surface, the balloon requires a heavily clad or an externally rigid structure. For the present application, in order to support heavy generating components, such as generators and transformers, the balloon has to have strong internal structure as well. The pressure change at high altitude also creates a problem.

The cost of large-sized balloon fabrication is also a negative factor to the airship concept. As will be seen later in Section 7, the balloon requires the substantial part of the overall TWES cost. Furthermore, a periodic helium supply is tedious and costly.

3.3 HYBRID CONCEPT

The various limitations and disadvantages of the balloon concept have led us to combine a wing with a balloon. Such a configuration is called hybrid (see Figure 3.1(c)). For the deployment and landing or operations in the low wind condition, the balloon lift is used whereas once the air station reaches the upper wind zone, the wing takes over its role. The design criteria of balancing the size of balloon and wing can be set in such a way that the minimum lifting force should be provided by the balloon which holds the air station at a certain low altitude, e.g., 3000 meters. This lifting force is thus used for safe deployment and landing, as well as for a safety lifter at the low wind speed. Typical reductions of airframe size for the hybrid system are indicated in Figure 3.3.

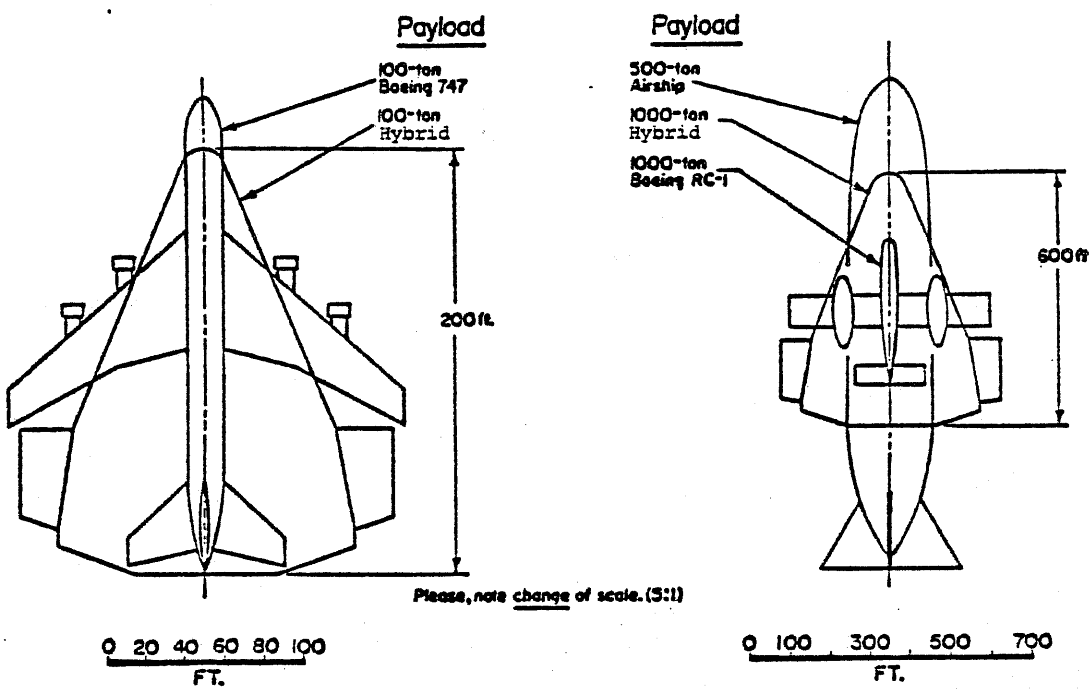


FIGURE 3.3 Hybrid size and payload comparisons (Miller, Proceedings of the Inter-agency Workshop on LTAV, Edited by Vittek, 1974)

Current technology for the hybrid system is not quite advanced enough to build a large scale hybrid airship. A new development for the design and fabrication technology is thus necessary. Even though the reduction of balloon size could be achieved by combining the wing, the cost associated with the hybrid system will remain high due to its inherent complexity.

3.4 VTOL

The basic safety and take-off/landing problem existed for the application of wing concept to the present TWES. This problem can be eliminated by employing the VTOL-like thruster arrangement (see Figure 3.1(d)). At the high wind operational condition, the system looks just like the wing lift-generation system in which the entire lifting force is generated by the wing. For the deployment/landing operations or the stall wind condition, the rotor axis is rotated to the helicopter rotor position (see Figure 3.1(d)). The generator/rotor function is now converted to the motor/propeller function by pumping electricity back to the system. The degrees of safety can be achieved by increasing the number of rotor-generator/propeller-motor system with the penalty of the weight and cost increase. Due to the added mechanical complexity of such a rotating mechanism and the multi-purpose rotor-generator/propeller-motor system, fabrication and maintenance could be somewhat costly. However, the VTOL technology has been developed and tested in military crafts, as well as commercially. Therefore, this concept is expected to have the best all around features to satisfy the requirements of TWES.

4.0 SUBSYSTEM

The components of the subsystem for TWES will be classified into two categories: one is mechanical and the other is electrical. The major mechanical components on the air platform are rotors, whereas the electrical components may vary, depending upon the method of power transmission from the platform to the ground station. A comprehensive study of the power transmission method for TWES was made by an Australian consulting company for the University of Sydney (1979). The criteria of the study was to determine a transmission method which would provide the best weight-to-power ratio with minimum power loss. We did not repeat such a study here but simply employed their recommended method for TWES. Essentially, this consisted of AC generators, transformers and rectifiers. The basic concept of this combination is well described in the report mentioned above. However, if one considers the following factors for the electrical system design, it will be a natural conclusion to have such a system as mentioned above:

i) high voltage transmission required for minimizing the loss through the tether cable, thus advantageous to use AC generators with step-up transformers, and

ii) elimination of generating conductance and inductance in the cable, minimizing the problem of synchronization (superiority of DC transmission).

We will now describe key features of selective components essential for our assessment study in the following section.

4.1 ROTORS

There are two basic methods of operating a wind turbine rotor, i.e., constant RPM or constant velocity ratio. Figure 4.1 shows a typical efficiency curve of a rotor as a function of λ, the ratio of the rotor tip speed to wind speed. C_p continuously varies with λ and usually provides the peak value at

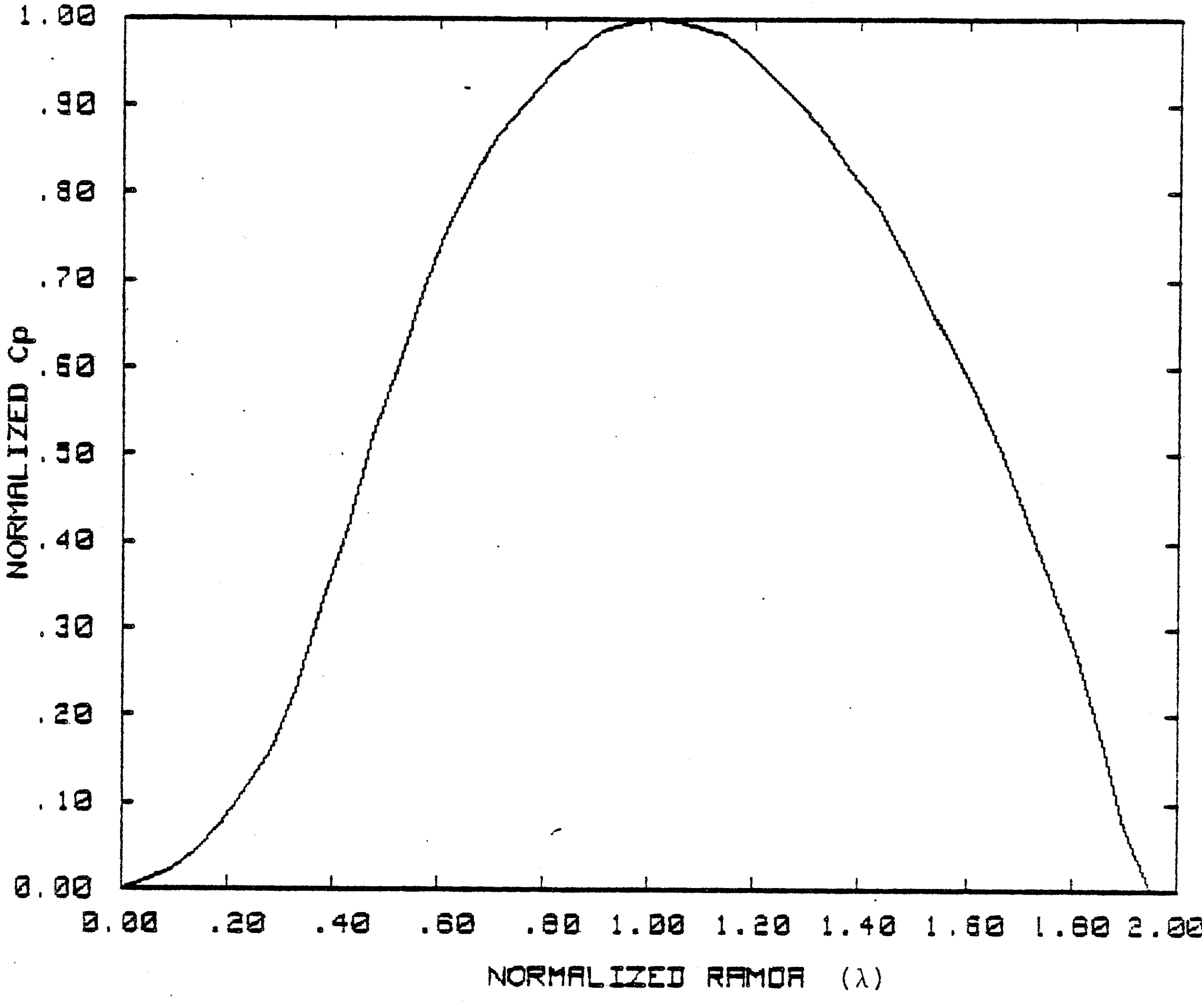


FIGURE 4.1 Normalized rotor power coefficients
($\lambda \equiv$ wind speed/tip speed)

a certain λ. For the constant rotational speed (CRS) operation, the efficiency of the rotor varies with wind speed, whereas for the constant velocity ratio (CVR) rotor it must adjust the rotational speed in order to keep the maximum rotor efficiency at all times.

Choice of an operating mode between these two should take various factors into account. First is the power output regulation of the windmill. From a system economy standpoint, the windmill is usually designed at a specific (or rated) wind speed for the rated power. Although the constant rotational speed operation will require blade pitch change to maintain the constant rated power, such a technique is widely used to date in propeller technology and therefore the reliability is well established.

The second factor for selection is related to generators connected to the rotors. It is readily understood that for the wind turbine applications constant rotational speed generators are superior to variable speed generators both in performance and operation. The weight and cost comparison of these two generators will also give an advantage to the CRS generators.

Furthermore, as is seen from the power and thrust curves in Figure 4.2, the thrust force at the constant rated power for the constant RPM mode is much smaller than that of the constant speed ratio. This point is particularly important in TWES in that the overall lift-to-drag ratio should be as small as possible to keep the catenary profile of the tethered cable upright.

It is for these reasons that we have chosen the constant RPM mode for the rotor operation, and used it through the current TWES assessment study.

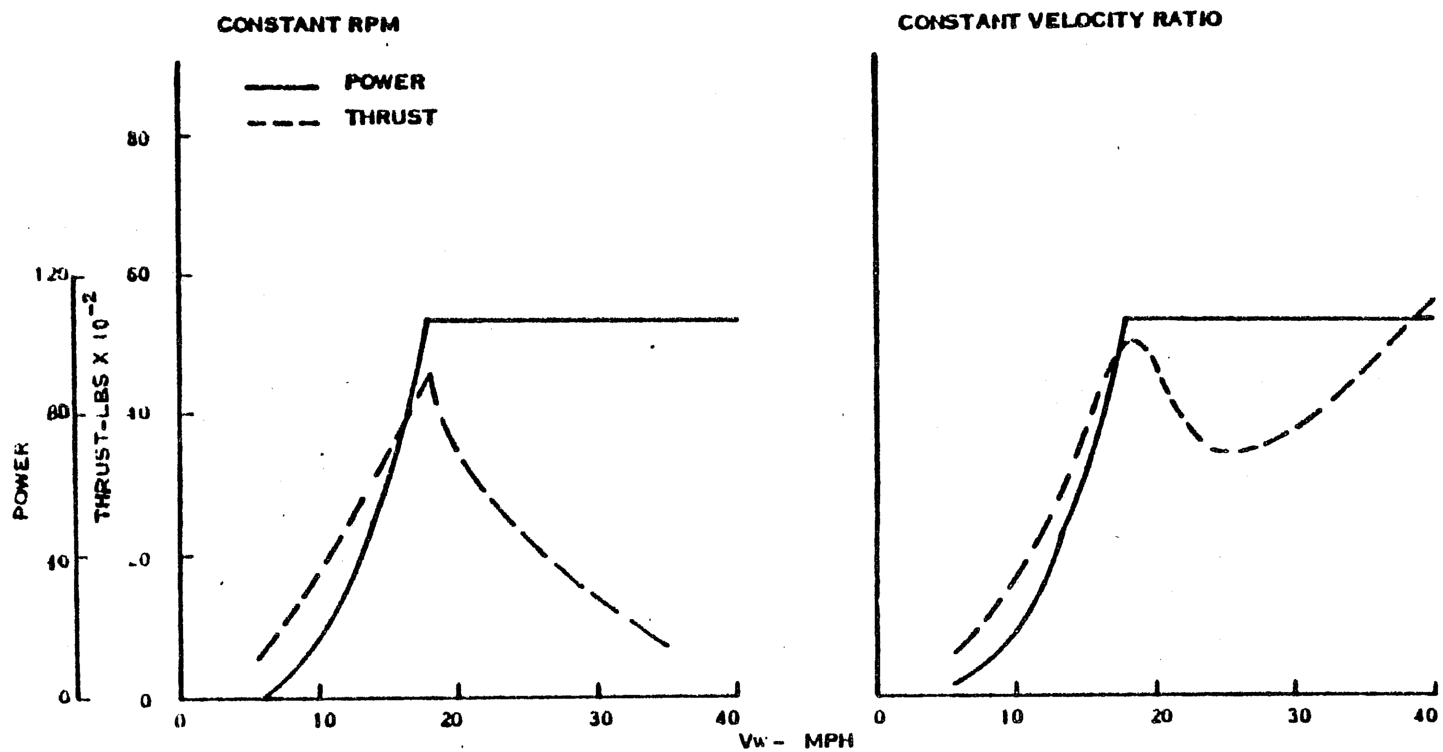


FIGURE 4.2 Thrust loads under variable pitch operation (G.E., 1976)

For the conventional wind turbine, the maximum power coefficient is limited to .40 ~ .45 at $\lambda_{opt} \sim 10$. Significantly higher efficiencies are reported by use of various augmented systems. The augmentation ratio is defined as the ratio of power output of an augmented system to that of a conventional turbine of the same diameter. Among many augmented systems, the dynamic inducer, diffuser augmented wind turbine, and vortex augmented turbines were considered. The dynamic inducer can be seen as a conventional turbine with the end plates or tip vanes at the tip of the rotor blades. These tip vanes induce increased mass flow through turbine. The augmentation ratio of about 1.6 can be achieved by the dynamic inducer (Lissaman, et. al., 1980). The Diffuser Augmented Wind Turbine (DAWT) system consists of a shroud (static diffuser) around the rotor. The diffuser increases the mass flow through the turbine by creating a region of low pressure behind the rotor. The augmentation ratio of 3.5 can be achieved with this method (Vas and Mitchell, 1979). The vortex augmented system utilizes a horizontal delta surface to create the vortex. The turbines placed in the vortex extract the power. This system is reported to have an augmentation ratio of 1.5 (Vas and Mitchell, 1979).

In the same wind environment, the diameter of an augmented system can be smaller in proportion to the inverse of the square root of the augmentation ratio. Higher efficiency of the rotor will provide savings of rotor component weight, as well as gear weight. The economical assessment study made on Augmented Horizontal Axis Wind Energy Systems (Harper, 1979) reported that the greatest hope for cost effectiveness was expected from Diffuser Augmented Wind Turbine (DAWT). Due to the highest expected and proven augmentation ratio and the better cost effectiveness, the diffuser augmented wind turbine is considered for the present TWES.

4.2 ELECTRIC SYSTEMS

The University of Sydney made an extensive study on the "on-board power plant" (see the report by Merz and McLellan and Partners (1979). Based on their work and our independent investigation, we have concluded that the A.C. synchronous generator/step-up transformer/rectifier-inverter system is the most advantageous for the high altitude wind energy application. Their recommended arrangement is shown in Figure 4.3.

Our concern for selecting various electrical components lies in the weight. The mass of the transformer can be considerably reduced by keeping the frequency higher. However, frequency output of the A.C. synchronous generator is given as

$$f = \frac{P}{2} \cdot (\text{RPM})$$

where f is frequency,
P is number of poles,
and RPM is the rated rotational speed of the generator.

It can be seen that the rotational speed or the number of poles has to be increased in order to generate with the higher frequency, but the weight of the A.C. synchronous generator increases with the number of poles. The higher input rotational speed can be achieved by use of the step-up gear transmission but resulting in a heavy weight.

It is quite clear that an optimization study for the design of the least mass gear/A.C. synchronous generator/transformer/rectifier is needed. Parameters for such study include

- o rated power
- o rotor rotational speed (input rotational speed to gear transmission)

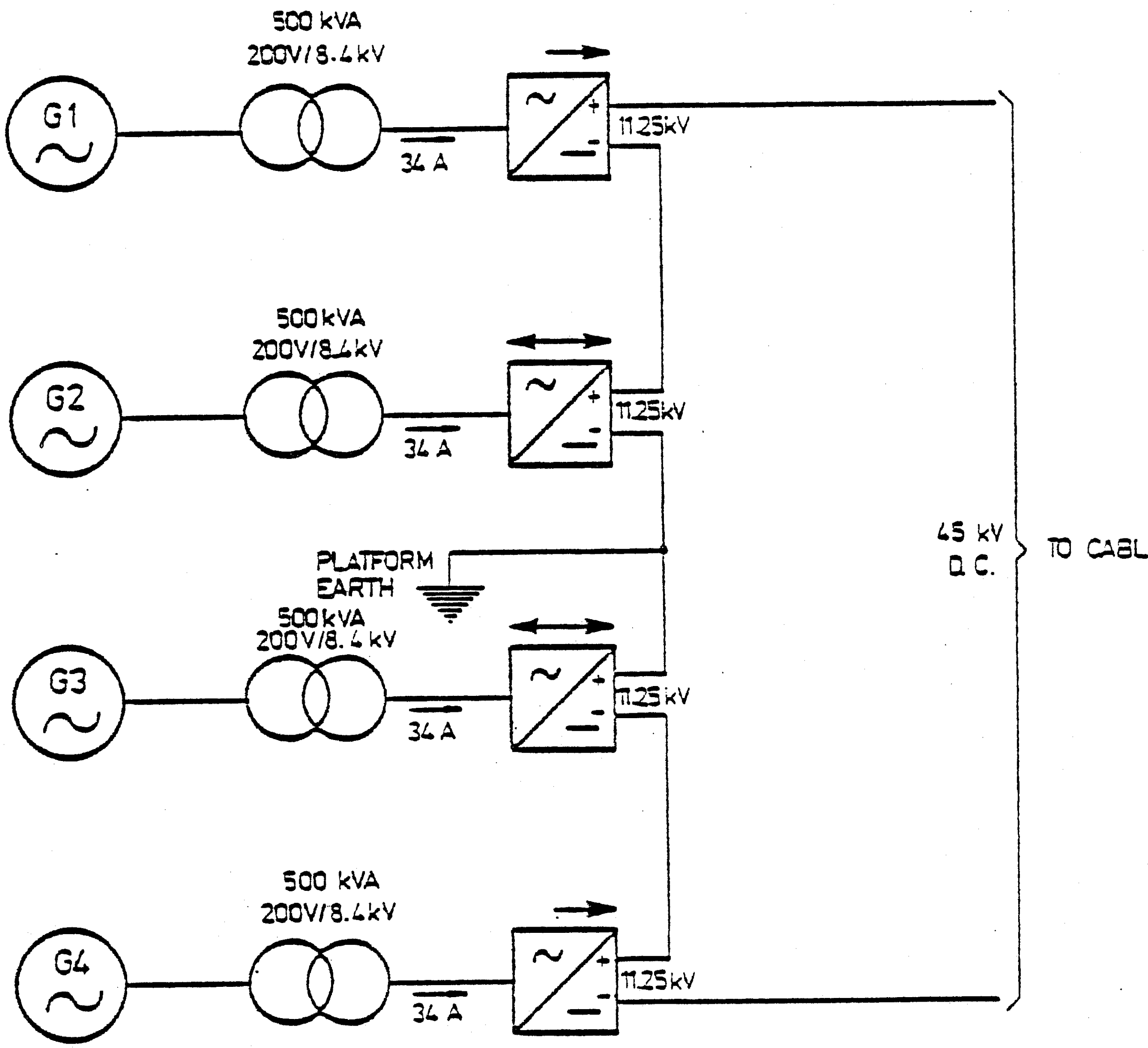


FIGURE 4.3 Recommended on-board power plant arrangement (by Merz & McLellan & Partners, 1979)

- o gear transmission gear ratio
- o number of poles (generator)
- o generator rotational speed
- o generator frequency

The Research Centre in Graz (1980) made a similar optimization study on the gear/generator system for their High Altitude Wind-Power Plants (HAPP).

Additional weight reduction can be achieved by utilizing the cold environment at the high operational altitude. The environment is especially advantageous in the design of the power transformer. The size of the required heat exchanger for the heat dissipation mechanism is expected to be reduced considerably. A similar consideration can be made for the rectifier circuit design.

5.0 SYSTEM ANALYSIS

Now that the basic conceptual design for TWES has been made, the next step will be to calculate the cost of electricity in a parametric analysis. In order to carry out such a calculation, the detailed characteristic for each component must be known. Since the objective of the present work is not to develop any new component particularly for the TWES, the existing state-of-the-art technology must be employed from the various sources of references and textbooks. After determining the performance characteristics for each component, we are ready to develop a simple computer program. In the following, the various performance curves, assumptions, etc., used for the calculation will be described, followed by the computer program development.

5.1 PERFORMANCE

5.1.1 Wind Distribution Data

The wind data used here were constructed from the high altitude wind data over the U.S. and North America presented by O'Doherty and Roberts (1981), as has been discussed before. For the present case of electricity assessment, New York, New York was chosen for the candidate site due to the highest annual energy density available, i.e., 16.2 kw/m^2 at 300 mb as is mentioned in their report (see Figures 2.5(a) and (b)). The air densities at each altitude were assumed constant over the year and taken from the Standard Atmosphere Table.

5.1.2 Aerodynamics of Rotor

Extensive design and performance analyses for the horizontal-axis windmills have been conducted to date under the direction of NASA. The performance curve for typical two-blade rotors is usually represented by a $C_p - \lambda$ graph, as shown in Figure 4.1. This nondimensional and normalized aerodynamic characteristic of the rotor was reconstructed from the data shown in the report of GE (1976). The reason for the normalization with respect to $C_{p\ max}$ and λ_{opt} in this figure lies in the fact that even for different geometric configurations of rotors, there exists a similarity in performance. Furthermore, for design work, we always seek the optimum tip-to-wind speed ratio, λ_{opt} with a rated wind speed specified. According to the GE report, for the two-bladed rotor having a typical geometric configuration, λ_{opt} is about 10, which provides the best C_p. As λ differs from λ_{opt}, $C_{p\ max}$ also declines accordingly. The actual value of $C_{p\ max}$ varies also depending upon the augmentation methods used here. $C_{p\ max}$ for regular wind is around .4 to .45. As has been mentioned in Section 4.1, however, the merit of using an augmentation method is substantial. We thus have used $C_{p\ max} = 1.0$ throughout the study by assuming an augmentation ratio of 2.5 of DAWT.

5.1.3 Mechanical Power Transmission

The mechanical power generated on the rotor shafts is transmitted through step-up gear transmission in the form of radial torque at a constant rotor shaft speed. The step-up gear is absolutely necessary for this type of windmill in order to match with the optimum range of rotational speed for the generator. For example, if one chooses the rated wind speed of 40 meters per second and the rotor diameter of 7 meters, the rotational speed must be about 410 rpm in order to limit the tip speed to 150 meters per second*. The regular generator for the ground windmill station has the standard rotational speed of 1800 rpm. On the other hand, the generator to be used for the air station will be of light-weighted aircraft type which has the rotational speed of 6000 rpm. It has clearly been seen that the use of a step-up gear is an absolute necessity.

* The report of Riegler and Riedler (1980) pointed out that that the undesirable blade vibration problems might occur if the blade tip speed exceeds about 150 meters per second.

The rotor shaft torque, speed, and generator shaft speed will define the gear transmission requirements such as size, speed, step-up ratio, the number of stages and the rated efficiency. Typical high quality or aircraft quality gear transmission provides the rated efficiency of .98 or better if it requires less than three stages. For the present system, therefore, the aircraft quality gear transmission was assumed for TWES. The power absorption due to the oil pump and the control actuator hydraulic pump for lubrication purposes was not included. However, generally the power drained for these accessories is less than .5% of the rated power at fully loaded condition. The computer model assumed a typical efficiency curve as a function of the percent of the rated loading of Figure 5.1 for the performance of a gear transmission.

5.1.4 Generator

The efficiency characteristics of generators vary considerably with both the type and size of the machines, as well as from one design to the other. The computer program assumed a synchronous A.C. generator which provided the variation in efficiency as a function of percent of the rated power (Figure 5.2) and efficiency corrections for the variations in the rated power (Figure 5.3).

Due to the weight conservation necessary for the airborne system, a 400 Hz aircraft type light-weighted A.C. generator was considered. The rated efficiency for the aircraft type generator is only on the order of 85% and this low efficiency is attributed to the small size (about 100 kw usually and very rarely 500 kw) of such generator. The trend of rapid efficiency decline is seen even in the regular A.C. generator (see Figure 5.2). When the higher rated generator of this type is developed, such as 500 kw or higher, such a generator is expected to have a similar performance curve as shown in Figures 5.2 and 5.3. We therefore used the performance curves

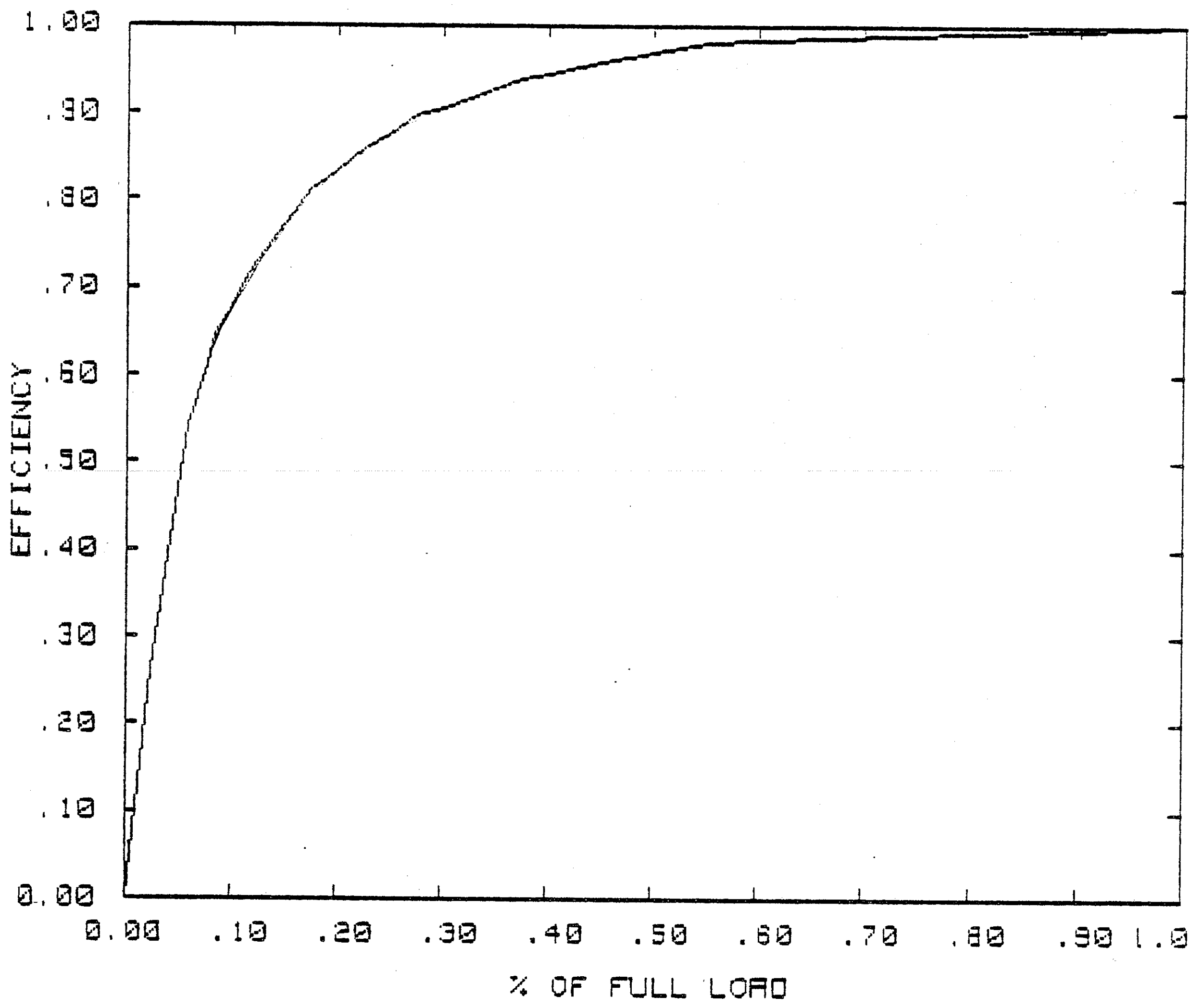


FIGURE 5.1 Efficiency of gear transmission

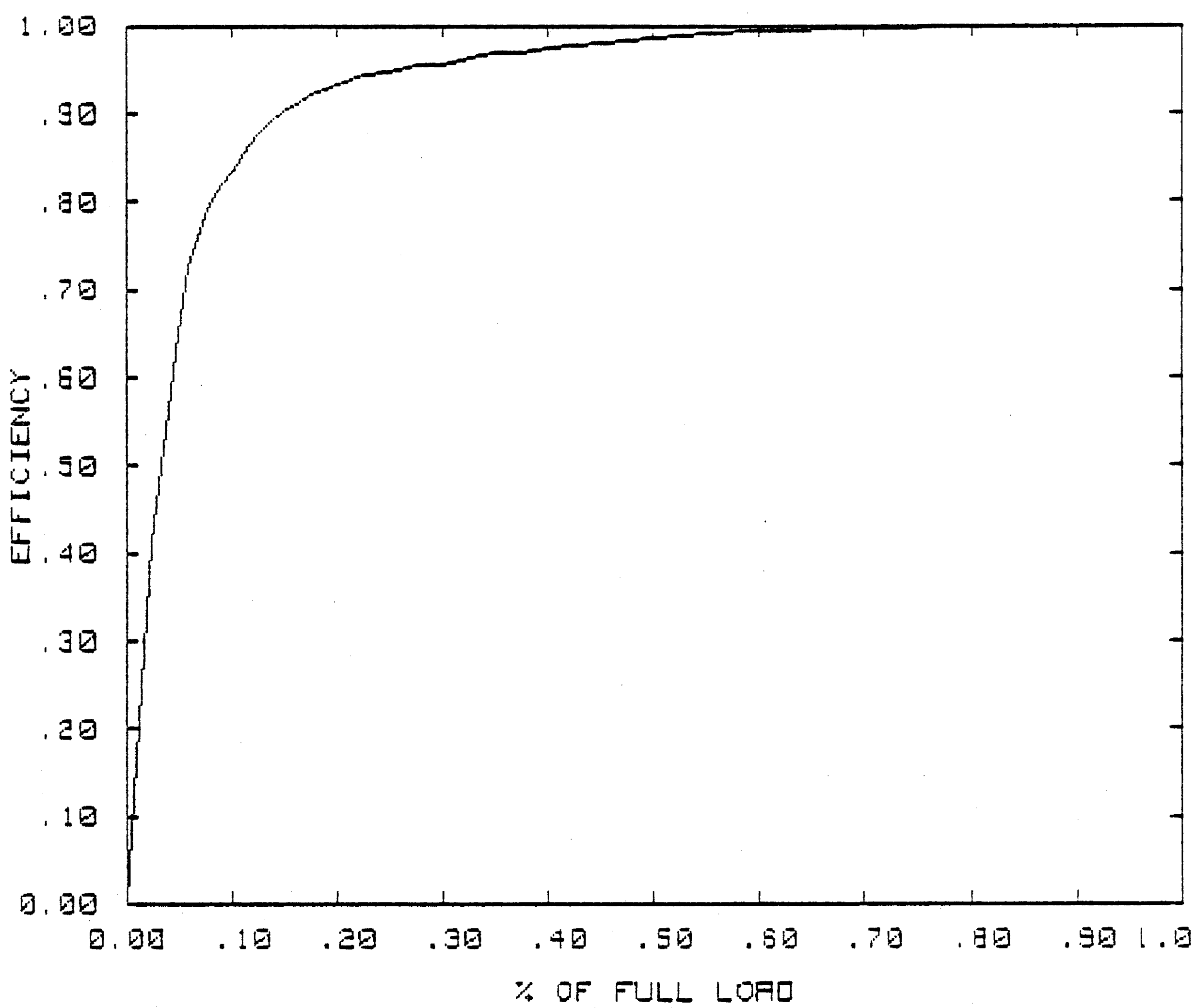


FIGURE 5.2 Efficiency of synchronous generator

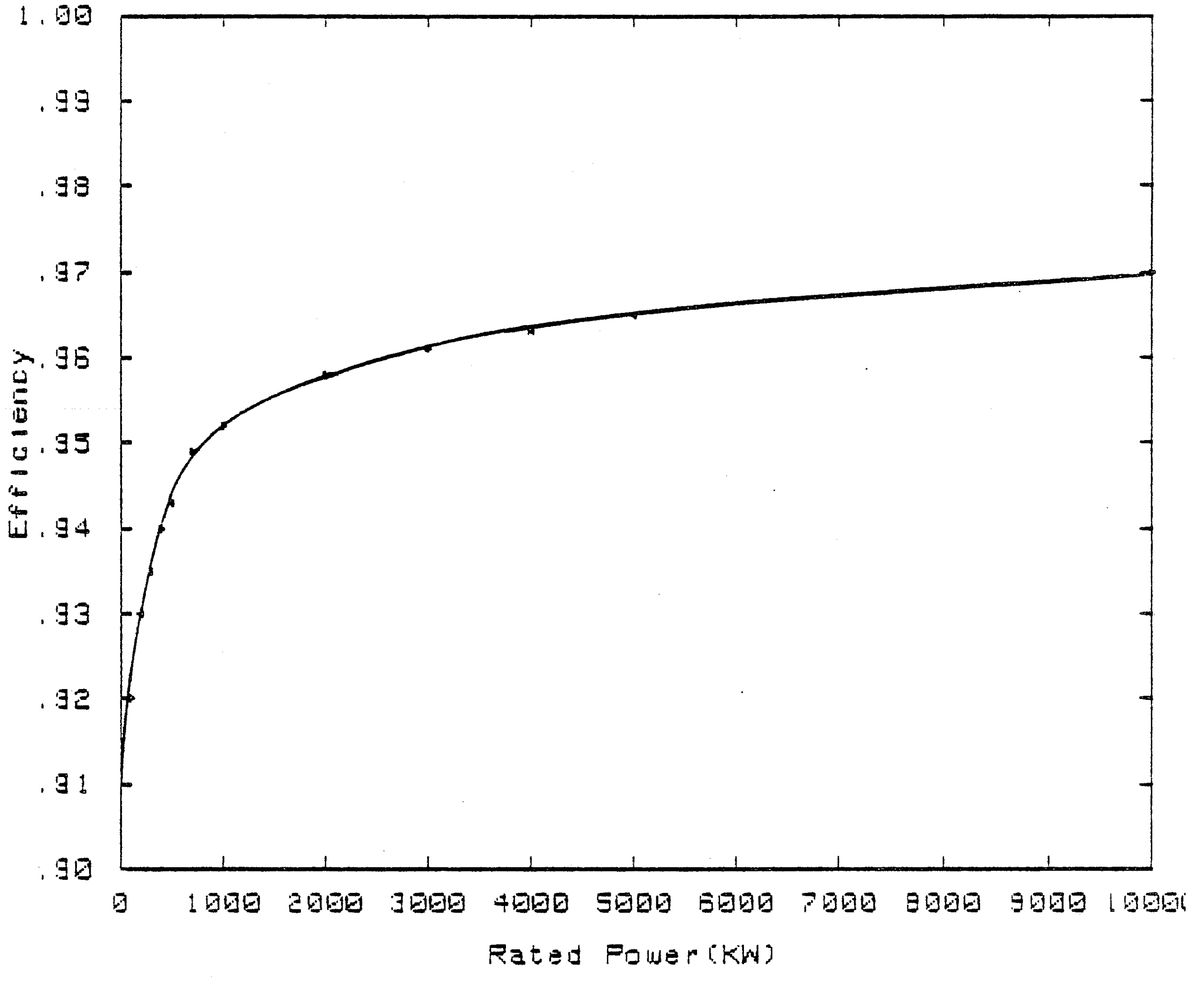


FIGURE 5.3 Efficiency of synchronous generator at rated power

in these figures for the present analysis. Finally, losses due to the regulator were not counted in the program.

5.1.5 Transformer

Similar to the generator, the transformer losses are a function of size and actual power output. At rated power the loss may be expressed as a fraction of input power as:

$$\text{Loss} = .0153 \left(\frac{1000}{P_R}\right)^{.21}$$

where P_R is rated power in kw.* By using this formula the rated efficiency as a function of the rated power was recalculated and is shown in Figure 5.4. Transformer loss at partial power also exists, however, in a practical sense the efficiency is very close to being constant, as that of the fully loaded condition. Therefore, the efficiency of the transformer at the fraction of the rated power was assumed to be constant in the present study. Again, in order to save component weights, the transformer for future use with TWES will require a new design of development. The low-temperature environment prevailing at TWES operating condition is considered to be highly favorable for the transformer's heat exchanger. A compact and light-weight transformer design will be possible, but in the present study, such assumptions were eliminated.

5.1.6 Rectifier and Inverter

Due to the high efficiency and light weightness, the solid-state technology was considered to be applied. The program assumed the efficiency of the rectifier-inverter circuit to be .98 for all cases. It must be pointed out that the solid-state rectifier-inverters currently existing are of small size and, therefore, that of high power must be newly developed for TWES.

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* The expression for the transformer loss is found in G.E. report, 1976.

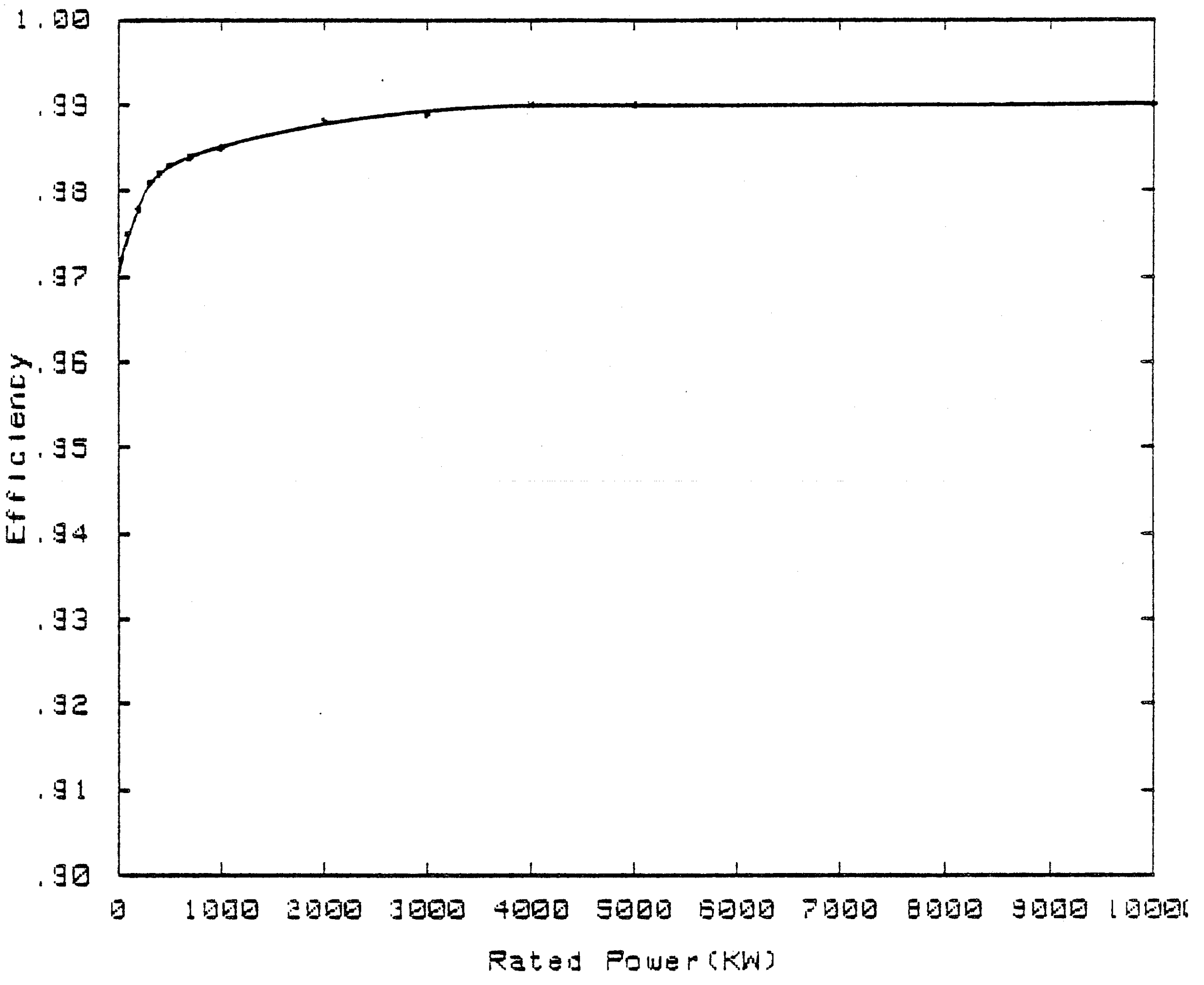


FIGURE 5.4 Efficiency of transformer at rated power

5.1.7 Transmission Cable

The electricity loss in the cable depends on the cable cross-sectional area, transmission voltage, and cable length. Figure 5.5 shows a calculated relationship between the loss and cable geometries. The present computer program assumed the length of the cable to be a function of the operational altitude. The type of conducting material to be used was aluminum in order to reduce the cable weight. Transmission voltage and the transmission efficiency could be varied for the parametric study. However, 35 KV was assumed for the transmission voltage and .95 was assumed for the transmission efficiency throughout the study as was recommended in the report by Merz, et. al. (1979). Therefore, the cross-sectional area of the conducting material (or mass of conductor) was determined as a function of the cable length.

Another aspect to be considered here is related to the high power transmission in the singular cable, namely corona discharge or voltage breakdown problem. When Kevlar is used for insulation in the coaxial cable configuration, the disruptive critical voltage V can be determined as follows:

$$V = \varepsilon\, a \ln \frac{b}{a}$$

where ε = the maximum dielectric strength of Kevlar (= 37.68 MV/m)

a = core cable radius (m)

b = inner radius of outside conductor (m).

In determining the coaxial cable diameter, the thickness of Kevlar insulation is always monitored in the present analysis. It turned out, however, that the amount of Kevlar material needed for the mechanical strength always exceeded that for prevention of corona discharge. This feature particularly owes to the high dielectricity of Kevlar material.

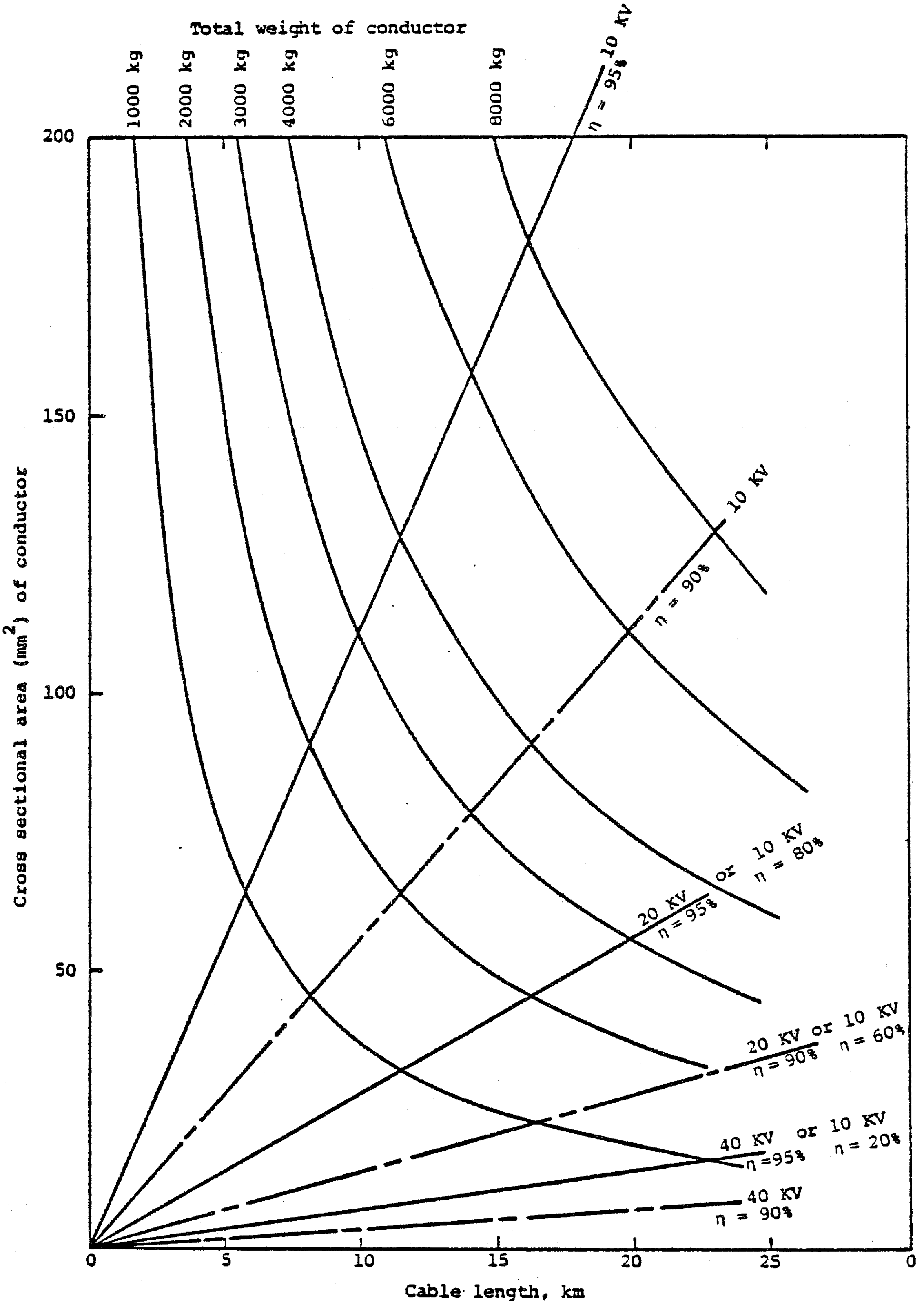


FIGURE 5.5 Relation of aluminum conductor sizes and the efficiencies

5.1.8 Aerodynamics of Platform and Tether Cable

As has been mentioned earlier, the VTOL platform was considered for the economical assessment of TWES. The wing was assumed to generate the entire lifting force required for the power generation mode. In case of the wind speed becoming below the stall speed of the wing, the integrated rotor-generator assembly is rotated about its mounting axis and provides the upward thrust like helicopter rotors with electricity fed back to the generator. The same operational procedure will be taken for the take off and landing of the platform.

The key aerodynamic considerations to be given for the platform should include the following aspects:

i) relationship between L/D and cable profile,
ii) lift control mechanism for station keeping
iii) cut-off/cut-in operations and
iv) aerodynamic stability of the platform.

The first aerodynamic design concern for the platform is related to the air platform station keeping at the rated wind speed and altitude, i.e., what size of the wing area is required? Although many parameters exist for determining the wing area, the value of lift-to-drag ratio* at the platform plays a most essential role in this respect. In order to maintain tether cable profile in rather vertical position, L/D at the top must have a reasonably large number. Otherwise, the incidence angle of the cable at the ground station would become too shallow. The high voltage cable hanging near the ground for a long distance would be extremely hazardous to nearby environments. In our study the minimum cable angle made with the ground was limited to 35 degrees. In order to

* The definition of L/D at the platform is the ratio of excess lift (i.e., lift minus weight) to the total drag at the platform such as lift-induced, form, skin and power-generation induced drags.

achieve this goal, we exercised the existing cable dynamic computer code available at Tetra Tech at various altitudes by changing the wind distributions, L/D and cable diameters. It was discovered that within the possible wind speeds and altitudes we encountered for the present TWES study, the L/D value must have been unity or larger.

In developing our computer program then, we chose L/D to be one. This made the design procedure for determining the wing area substantially simple. Once the rated wind speed and power are specified, the aerodynamic drag forces D are readily determined by adding the negative thrust forces on the rotors to the aerodynamic forces on the other air components. The negative thrust forces acting on the rotors are calculated from the thrust coefficient-λ curve as are shown in Figure 5.6. The determination of the aerodynamic drag of the platform is rather straightforward except that the drag on the wing is not known in advance. Therefore, the drag on the wing must be assumed first and then checked for its accuracy after the wing area is determined.

The lift control mechanism such as flaps or ailerons are necessary to keep the airstation at the desired altitude for varying wind speeds. For the wind speeds higher than the rated speed, the wing generates much higher lifting forces than required, sending the airplatform to a higher altitude, whereas for the lower wind speeds, the airplatform tends to fall down. From the power generation point of view it is desirable to keep the constant operational altitude of the platform as much as possible and thus the lift control device is a necessity. From our long experience in aircraft technology, it is a well-known fact that the maximum lift coefficient can be taken to be twice that of the normal operation (see the wing data in the book of Abbott and Doenhoff (1959)). We therefore chose in our study the lift coefficient at the design point, $C_L = 1.0$ and the maximum lift coefficient,

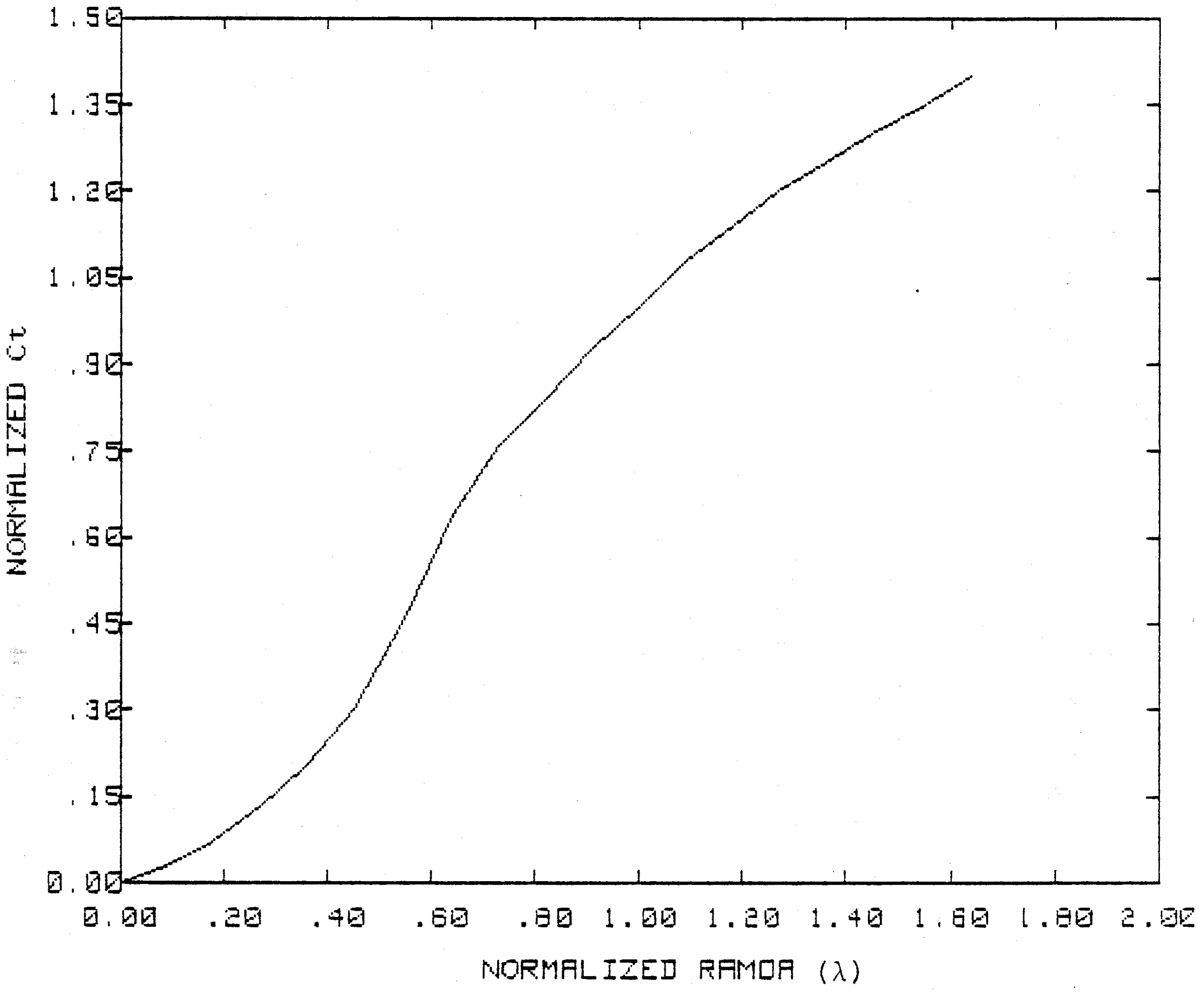


FIGURE 5.6 Normalized rotor thrust coefficient
($\lambda \equiv$ wind speed/tip speed)

$C_{L\ max} = 2.0$. The lift coefficient can be adjustable by means of, e.g., flaps over a range of 0 to 2.0. It must not be misunderstood, however, that the airstation can be sustained at the design altitude only until the wind speed there reduces to $V_{rated}/\sqrt{2}$ or .707 V_{rated}. The station-keeping in the present problem involves the problem of tether-cable dynamics, unlike the airplane. As has been mentioned before, the station-keeping is related to L/D. For a lower wind speed, D reduces faster than L due to the faster reduction of the negative thrust forces than that of wing lifting forces. It means that the lowest wind speed for the platform to remain at the design altitude is much less than .707 V_{rated}, which must be calculated from the relationship in L/D. Such V will then determine the cut-in wind speed at the lower wind side and eventually will be used for calculating the total energy.

Study for the stability of the air platform will require a substantial effort by applying the equation of motion in six-degrees of freedom. Such a study is beyond the scope of the current study, and is left untouched. However, it can be said that the static stability of yaw motion for the airstation will be secured by designing the platform in such a way that the negative yaw moment is generated. This will be achieved by placing the tether cable connecting point at a rather forward position while placing the rotors at a backward location.

Once the TWES's platform was designed, the cable dynamic program was used to verify the location (altitude and horizontal distance from the tethered point) of the platform and to calculate the cable catenary profile shape and tension. It was learned that for all of the cases studied here the ratio of the cable weight per unit length to the tension and the aerodynamic force on the cable were low enough that the cable profile shape could be approximated as a straight line. Kevlar co-axial cable with aluminum as a conducting material was considered for the system since this material provided the very high breaking strength to weight ratio.

5.1.9 Operational Duration

As was pointed out in the report of Furuya and Maekawa (1980), the upper wind energy available over the continent of North America during July is 1/27th that of January. Due to the present selection of VTOL concept for the lifting generation, the deployment of the station during the summer will be a big burden to the economy of the TWES since the electric power must be pumped back during such time. Before the wind energy data of the U.S.A. was made available by O'Doherty and Roberts (1981), we independently collected the detailed upper wind data at Nashville, Tennessee. Sample calculations were then made for the available wind energies both for periods of one year and nine months excluding June, July and August. It was found that the difference in these two available wind energies was about 5% (see Figure 7.4 for a better understanding). Furthermore, when we calculated the power outputs based on one-year and nine-month operations, respectively, the difference was found to be only about 2% (see again Figure 7.4). It is for this reason that we propose to deploy the TWES for a nine-month period excluding three months of the lowest wind energy. According to the study by Fletcher and Sapuppo (1981), the percentage of pumpback power is about 5% of the overall generated power. Since more than 50% of such pumpback power will be used during the above-mentioned months, we will be able to save a substantial amount of the electricity pumped back to the station with the 9-month operation of TWES.

Another merit of the nine month operation will be that we can utilize three months of platform-grounded time for repair and maintenance. This type of periodic check will increase the reliability and lifetime of the system.

5.2 WEIGHT

Weight is the most important factor for design of airborne equipment, since small additional components weights would increase the structural weight considerably. Weight data were obtained from various vendors, vendor catalogues, handbooks, and engineering assessments. Since in most cases they did not cover the complete λ range of variables, they were curve-fitted to provide functional relationships convenient for the computer model. Figures 5.7 through 5.9 show the collections of such weight data for various components. Table 5.1 is the summary of the analytical expressions of such components weights used for the present study.

The rotor weight equation was based on the simple first order estimation of the blade weight. The rotor was assumed to be made of two aluminum blades. The solidity of .03 was considered.[*1] The weight estimation of the gear transmission was made from the equation which was obtained by fitting the weight curve provided by a vendor.[*2] The output rpm of the gearbox was 6000 rpm in order to run the aircraft type A.C. synchronous generator. The step-up ratio was between 10 and 20 depending upon the rated wind speed to be selected.

The weight of the commercially available transformers is shown in Figure 5.7, but redesigning will be required to take advantage of the extremely cold environment. A substantial weight reduction due to a better heat exchange should evolve. However, since such data were not available at the time of the current study, the mass ratio of 2 KVA/kg presented by Merz and McLellan & Partners (1979) was assumed.

The weight of accessories for the generators and transformers such as regulators and rectifiers was not included in the

*1 See, e.g., Figures 3-9 and 3-10 in the report of Karman Aerospace Corp. (1976).

*2 The data include those provided by Philadelphia Gear Corporation.

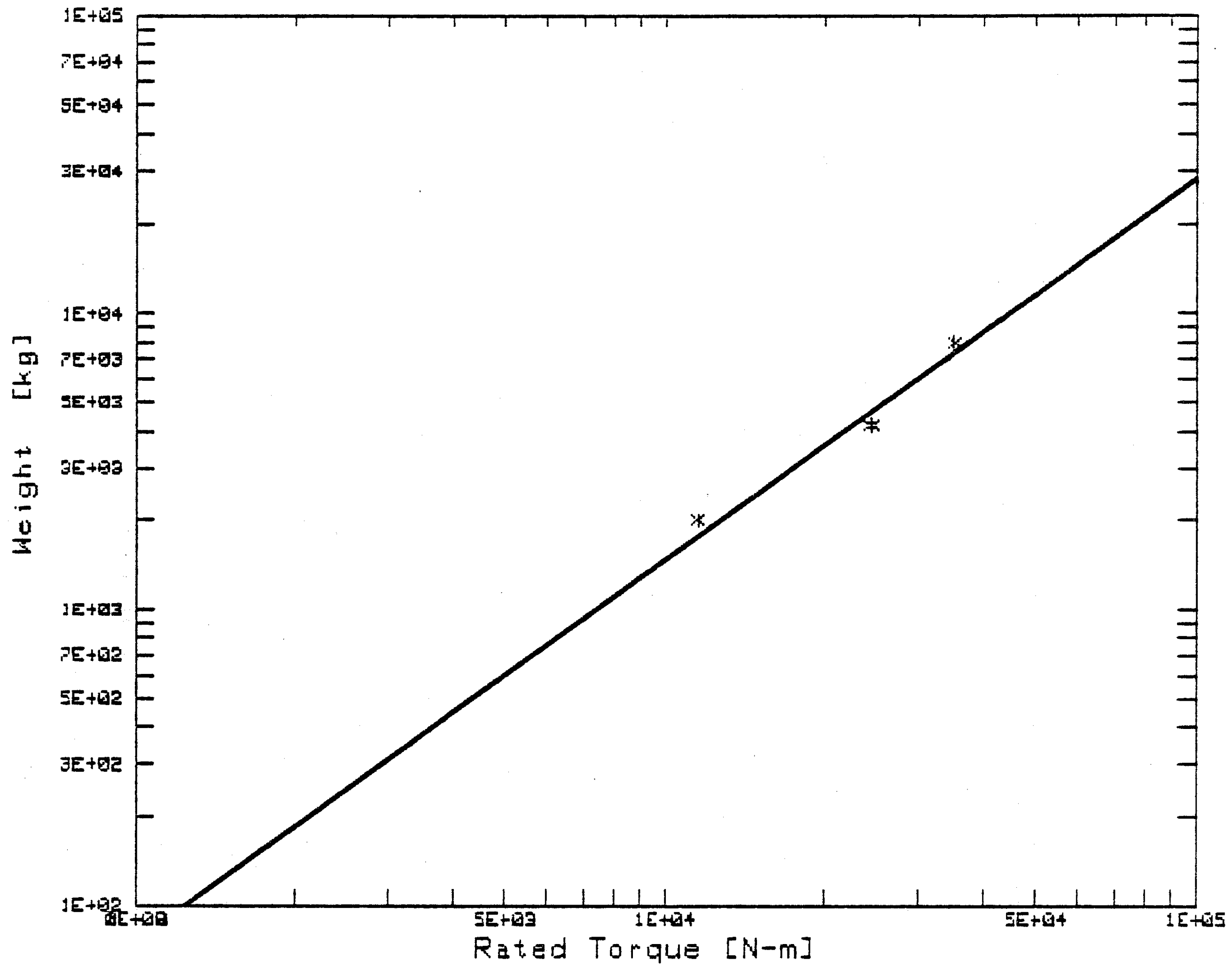


FIGURE 5.7 Weight of gear transmission

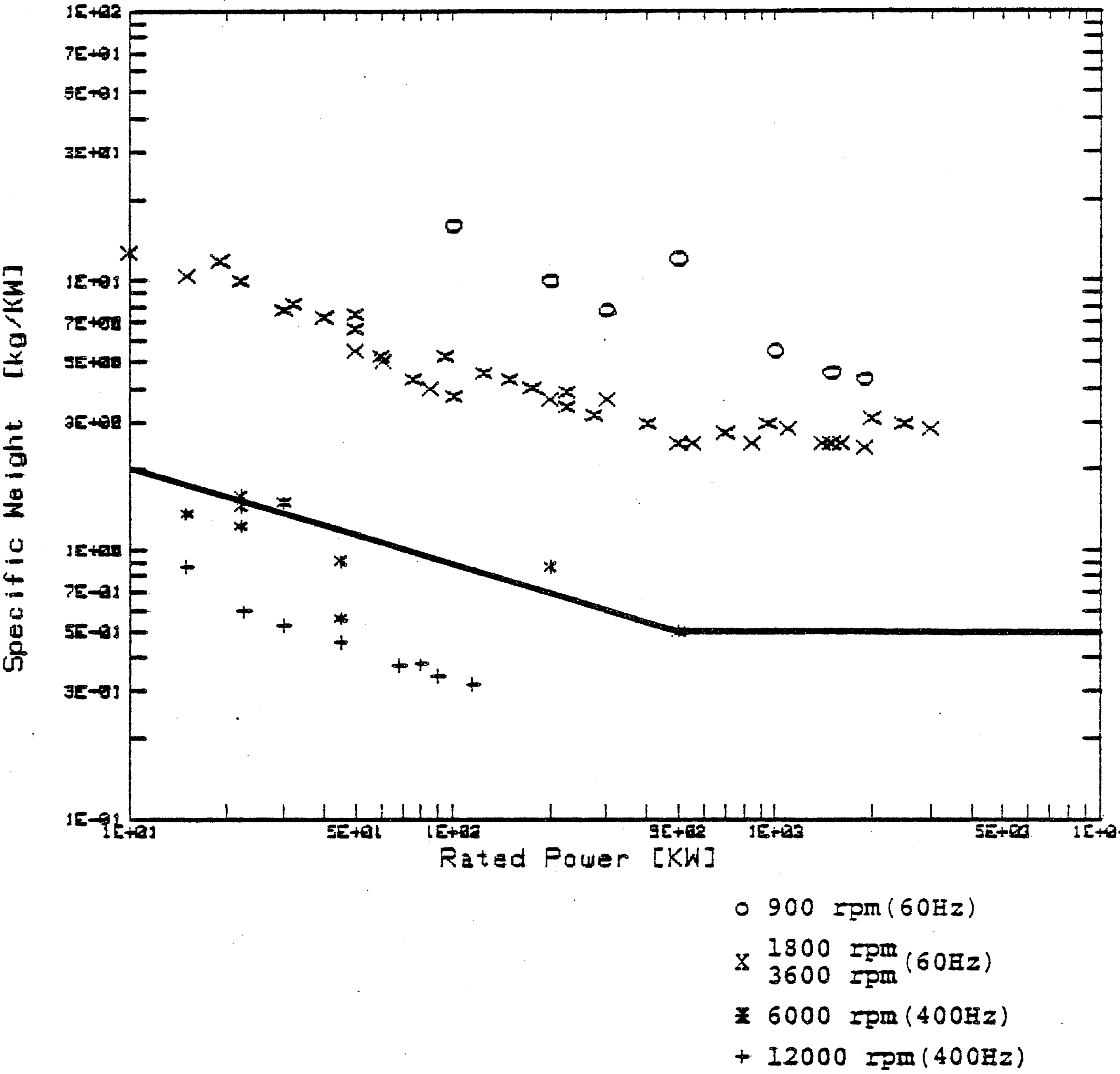


FIGURE 5.8 Specific weight of A.C. synchronous generator

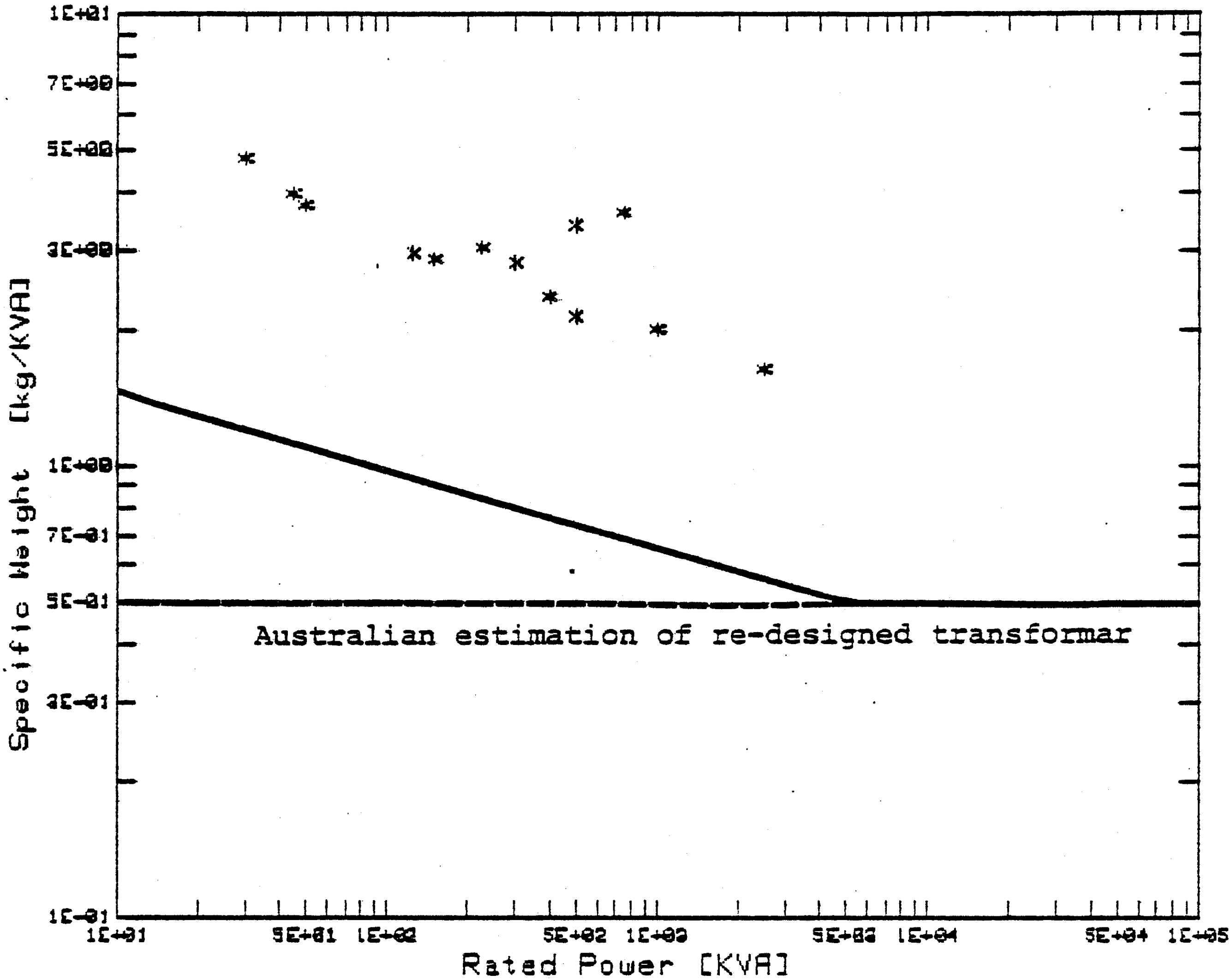


FIGURE 5.9 Specific weight of transformer

TABLE 5.1

SUMMARY OF WEIGHT FORMULAE

Rotor	$w_t = .5876D^3$		
Gearbox	$w_t = 0.0143Q^{1.255}$	(Figure 5.7)	
Generator	$w_t = 4.318\ P^{0.653}$	$(P < 500\ KW)$	(Figure 5.8)
	$w_t = .5P$	$(P \geq 500\ KW)$	
Transformer	$w_t = 2.364P^{0.75}$	$(P < 500\ KW)$	(Figure 5.9)
	$w_t = .5P$	$(P \geq 500\ KW)$	
Airframe	$w_t = 9.79\ S_{wing}$		
Shroud	$w_t = 9.79\ S_{shroud}$		

where

w_t = weight (kg)

D = rotor diameter (m)

Q = rotor torque (N-m)

P = power (kw)

S_{wing} = wing area (m^2)

S_{shroud} = surface area of shroud (m^2)

weight computation due to their small contributions to the overall system. Weights of appendages to platform structure, such as landing gears, slaps, VTOL mechanism, and fuselage structures, were integrated into the airframe weight. In order to provide an accurate weight estimate for the airframe of TWES, an extensive study will be required like that done by Blacker (1979). Due to the limited time available in the present project, we utilized the first order weight estimate technique for the airframe given by Muckrodt (1974).

5.3 COST

5.3.1 Component Cost

The cost estimate for the rotor was made based on that presented by Carson (1974) who made the cost estimate for the newly developed helicopter rotors. The cost was adjusted to the level of 1981 with an annual inflation rate of 10% and then was reduced by 50% by assuming a mass production of 100 lots.

The cost estimate for the gear transmission was made on the basis of the vendor's price quotes (see Figure 5.10). We again fitted these points with an analytical expression.*

Due to the limited availability of the larger aircraft type generators (see Figure 5.11), the cost equation for generators was constructed based on the same criteria as that used for the generator weight. The transformer cost presented in Figure 5.12 was obtained from vendor's catalogues. The cost formula was constructed based on these commercially available transformer costs rather than redesigned ones.

* The dusty cycle was considered in selection of the gear system by an engineer of a vendor and therefore reflected on the cost. Also, it must be pointed out that the loading change frequency on the system was found much lower in the wind energy stream than that of endurance limit or fatigue limit, i.e., 10^5 to 10^7.

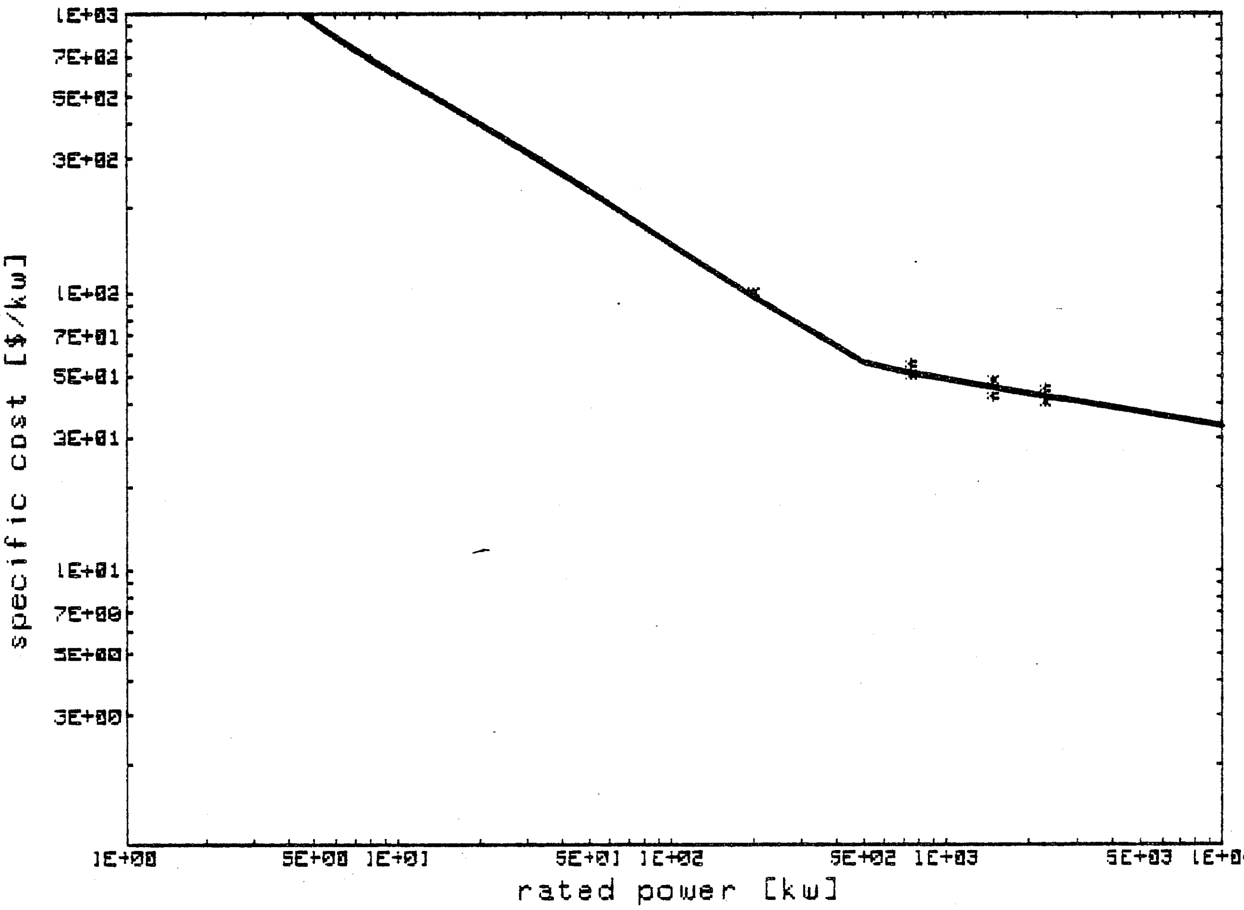


FIGURE 5.10 Specific cost of fixed gear transmission

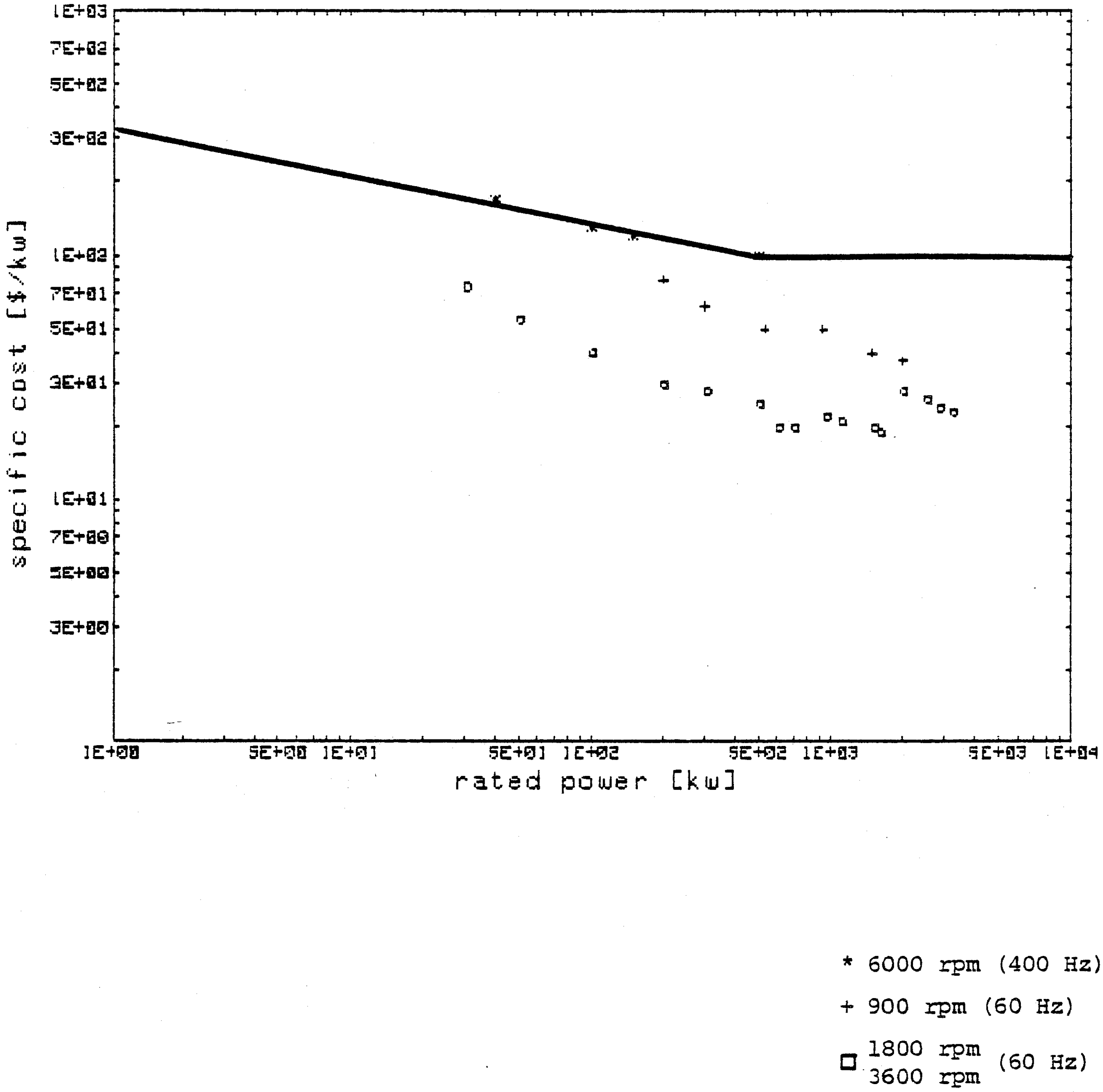


FIGURE 5.11 Specific cost of A.C. synchronous generator

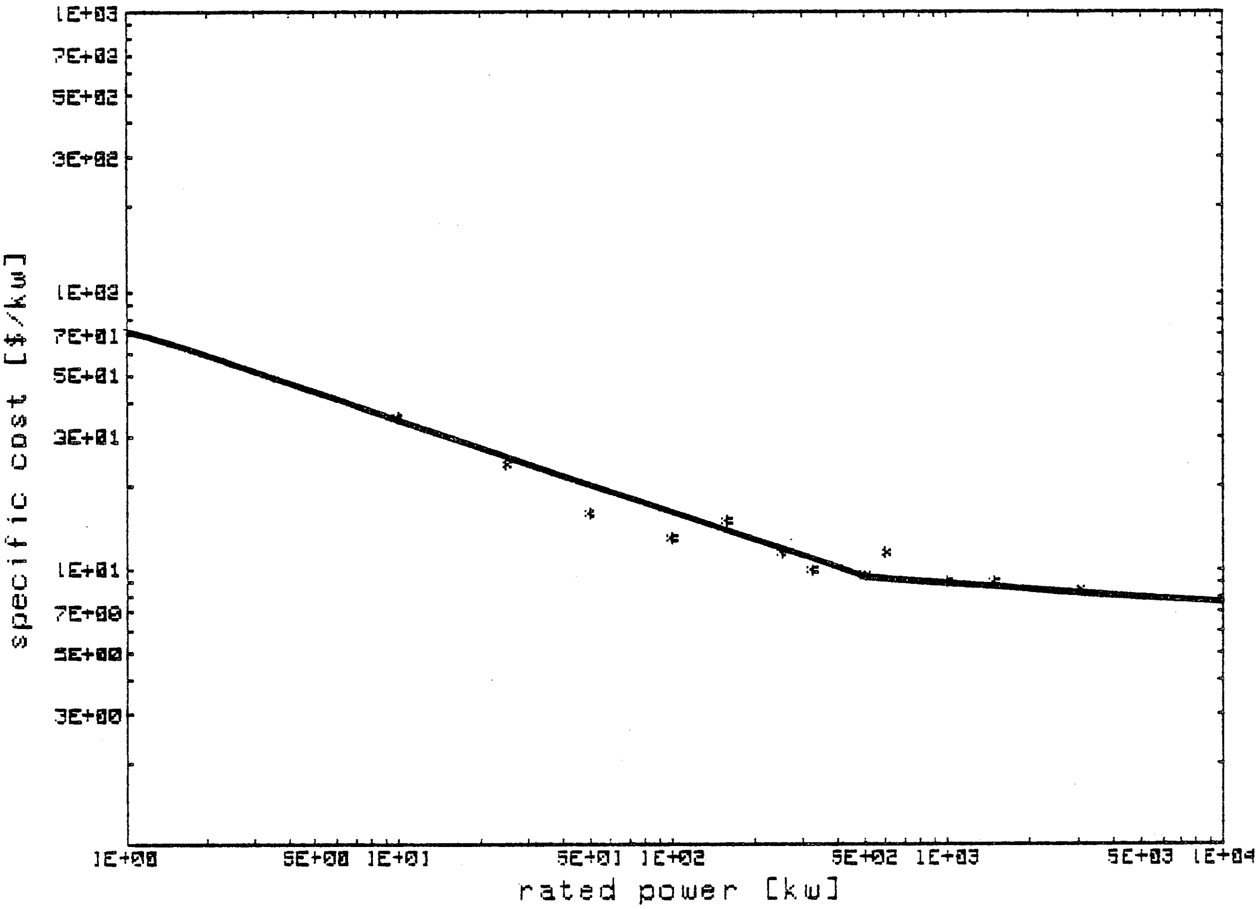


FIGURE 5.12 Specific cost of transformer

The cost of rectifier-inverters presented in Figure 5.13 was that of the Uninterruptible Power Supplies (UPS) which are commonly used for computers, on-line data processors, process controllers, etc.*1 The cost of the custom-design rectifier-inverter system for 100 lots will be expected to be reduced by 50%.

The cost of the airframe was again based on the first order cost estimate presented by Carson (1974).

The cable cost used here was that of Kevlar chord and aluminum wire, but didn't include any design cost.*2 The cost equation for the winch was made based on a vendor's price quote.*3 The cost formula used in the computer program was constructed on the basis of the above assumptions and are summarized in Table 5.2.

The cost of installation and delivery was estimated based on the extensive studies made for the large wind energy system (LWES). These include the paper by Thomas and Robbins (1979) of NASA who calculated the cost of transportation and installation of LWES to be about 30% of the overall machine cost. This percentage was considered to be applicable to the present TWES and was thus used.

5.3.2 Capital Cost

In order to assess the capital cost for a complete TWES on a production basis, it was assumed that the cost of each component was calculated based on 100 orders of each component. The capital cost is the sum of the individual component costs as well as assembly and transportation costs. The latter two

Note *1 See, e.g., the Standard Handbook for Electric Engineers, edited by Fink and Beaty (1978).
*2 A local vendor's quote such as Cortland Line Co., P.O. Box 1362, Cortland, New York 13045.
*3 E.g., Northern Line Machines Company, 1840 Marine View Drive., Tacoma, Washington 98422.

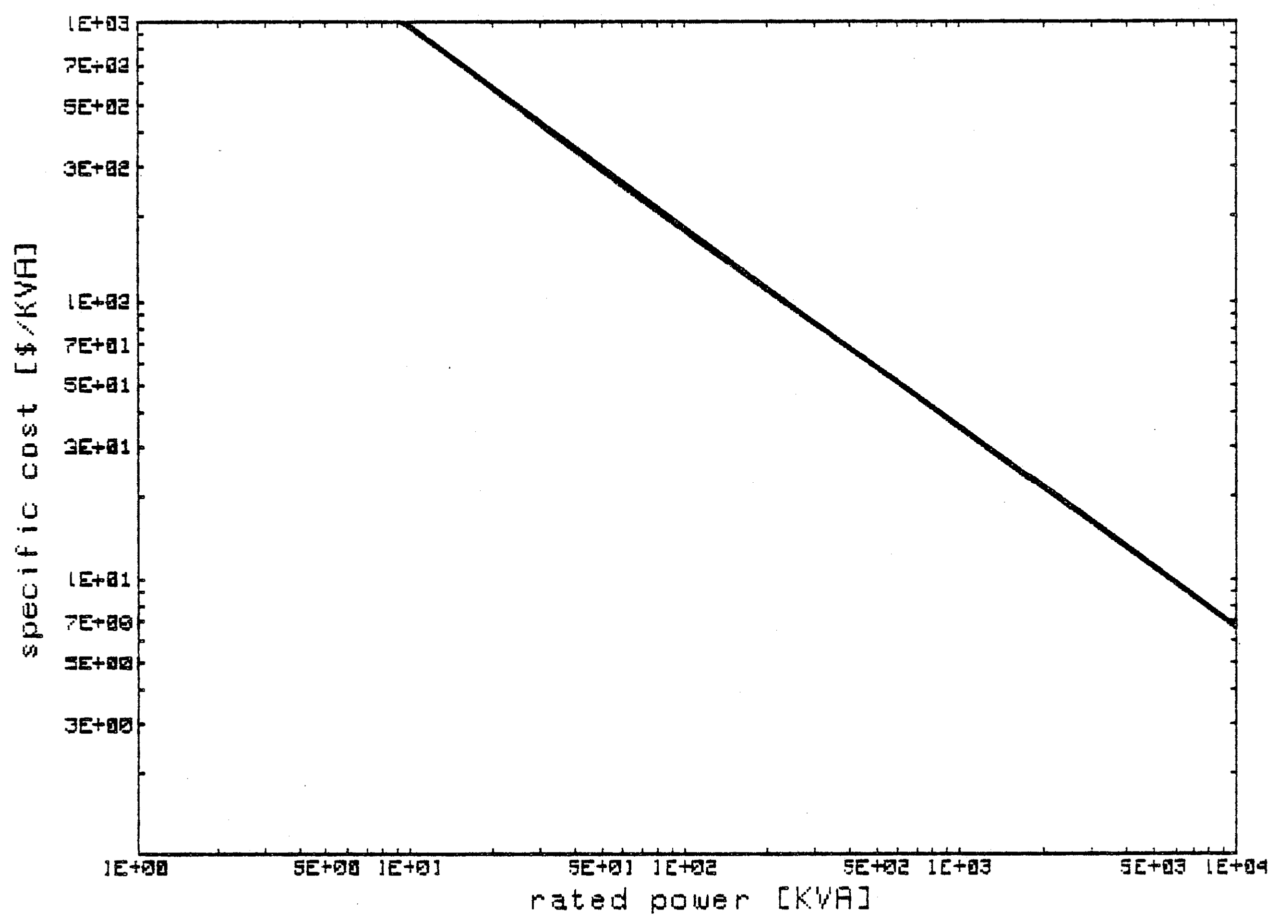


FIGURE 5.13 Cost of rectifier-inverter unit (production unit)
(constructed the data given in Standard Handbook for Electrical Engineers,1978)

TABLE 5.2

SUMMARY OF COST FORMULAE

Rotor	$C = 158\ w_t(\text{rotor})$		
Gearbox	$C = (2.323 \times 10^2)P^{.3977}$	$P < 500$ KW	(Fig. 5.10)
	$C = (1.405 \times 10^2)P^{.8491}$	$P \geq 500$ KW	
Generator	$C = (3.374 \times 10^2)P^{.8043}$	$P < 500$ KW	(Fig. 5.11)
	$C = 100P$	$P \geq 500$ KW	
Transformer	$C = 70P^{.6786}$	$P < 500$ KW	(Fig. 5.12)
	$C = 14.69P^{.9299}$	$P \geq 500$ KW	
Rectifier-Inverter	$C = 2500P^{0.600}$ (Fig. 5.13)		
Airframe	$C = 783.2\ S_{wing}$		
Shroud	$C = 3.437D^{1.2}$		
Tether	$C = 22\ w_t(\text{kevlar}) + 17.6\ w_t(\text{aluminum})$		
Ground Facility*	$C = (4.39 \times 10^{-4})\ T_{tether}\ L_{tether}$		

where C = cost (dollars)

$w_t(\text{rotor})$ = rotor weight (kg)

P = power (kw)

S_{wing} = wing area (m^2)

D = rotor diameter (m)

$w_t(\text{kevlar})$, $w_t(\text{aluminum})$ = weights of kevlar and aluminum (kg), respectively

T_{tether} = tension of tether cable (N)

L_{tether} = length of tether cable (m)

Note *1 This includes winch system and frames costs consisted of about 30% of the overall capital cost (see the paper by Thomas and Robbins (1979)).

5.3.3 Operation and Maintenance (O&M) Cost

During the Mod-2 design, Boeing performed detailed O&M estimate studies for the production of wind turbines operating in a 25 unit cluster. They estimated O&M cost to be approximately 1% of the capital costs. In case of TWES, however, maintenance of platform and ground station has to be considered, as well as that of the rotor-generator subsystem. When one considers the maintenance cost of the aircraft which operates in a similar condition to TWES, it is readily understood that such cost depends upon operational speed, loading, operational hours, and frequency of the take-off and landing. The operational speed of TWES is substantially lower than that of any commercial air transports. The loading of wing per unit area is also considered to be lower. On the other hand, TWES operates for approximately 6,570 hours per year, assuming nine-month operation of the system. This operational hour is $8 \sim 12$ times higher than that of commercial aircraft. Some difference also exists in the number of take-offs and landings. TWES is assumed to be deployed and retracted only once a year (for summertime in the U.S.), whereas commercial transports make about 1,500 take-offs and landings per year. This is considered to be the major factor for the aircraft maintenance cost to be 3% of the capital cost. Despite the additional contributing factors such as less mechanical complexities and less personal safety device requirements for TWES, we considered 3% of the capital cost for O&M costs in the present study.

5.3.4 Cost of Electricity

The cost of electricity (COE) produced by wind turbines is now computed as follows:

$$\text{COE (cents/kwh)} = \frac{(\text{Capital cost, \$})(\text{Fixed charge rate, \%})}{(\text{Annual energy, kwh})}$$

$$+ \frac{(\text{Annual O\&M costs, \$})(\text{levelizing factor})\ 100}{(\text{Annual energy, kwh})}$$

where the following explanations will be given for the fixed charge rate, levelizing factor and annual energy.

Fixed Charge Rate

The fixed charge rate (FCR) is a capital levelizing or annualizing factor which accounts for the return to investors, depreciation, allowance for retirement dispersion, income and other taxes, and other items such as insurance and working capital. It is a function of the design life of the unit, the general inflation rate, the debt/equity ratio of the utility and other financial parameters such as the weighted average cost of capital.

A fixed charge rate of 18% has been assumed in computing the COE for large, horizontal-axis wind turbines. This is a representative value for investor-owned utilities, assuming a general inflation rate of 6%, no allowance for tax preferences, an after-tax weighted average cost of capital of 8.0% (10% before tax) and a 30-year life.

Levelizing Factor

In order to correctly compute the total levelized revenue requirement or COE of a wind turbine (or any utility powerplant for that matter), expenses such as O&M costs which will tend to increase with time due to inflation (and thus result in a variable stream of annual costs) must be levelized before adding them to the levelized capital investment.

Levelization of expenses can be accomplished by multiplying the first year's expense by a levelizing factor. The levelizing factor is a function of the general inflation rate, the cost of capital and any real escalation (above inflation) to which the expense may be subject. Using the assumed values of economic parameters described above and a 0% real escalation rate on O&M costs, the corresponding levelization factor is 2.0.

Annual Energy

The annual energy output for any horizontal-axis wind turbine can be computed for a specific wind speed duration curve by computing the power output at each wind speed and integrating it over the appropriate time duration for each wind speed. Then it is multiplied by the annual availability of the turbine, usually 90%.

6.0 COMPUTER PROGRAM

Three computer programs were used for the current study. Two of them, Program I and Program III, were developed particularly for the TWES program. These were written in BASIC language and the computations as well as some of the plottings were made on Hewlett-Packard Series 9800 System 45 Desktop Computer, here at Tetra Tech. Program II is an existing cable dynamic program of Wang (1977), written in FORTRAN. The computations with this program were made by connecting our terminal with CDC 7600 at the SERI Computer Center.

The procedure of the computation is shown in Figure 6.1. Program I, system component design program, determined the configuration of platform, aerodynamic characteristics, and the capital cost of platform from various input parameters. Then, the aerodynamic characteristics of the platform were inputted to the cable dynamic program, Program II, to find the accurate cable conditions such as tension, position, and the angle between the cable and the horizon. If the results of the cable dynamic program showed undesirable conditions of the tether cable, Program I was used again to redesign the platform. Otherwise, the capital cost of the system, aerodynamic, mechanical, and electrical efficiency were inputted to Program III, the economical assessment program, to obtain the plant factor, capacity factor, and cost of electricity.

6.1 PROGRAM I (SYSTEM COMPONENT DESIGN PROGRAM)

The structure of the program is shown in Figure 6.2. The major inputs to this program include rated altitude, rated wind speed, number of rotors, and rated power. With these input data and assumed wing area to start with, the program calculated the system's weight, lift and drag force. Then the program determined the ratio of excessive lift to drag ratio and re-calculated the wing area needed for L/D = 1.

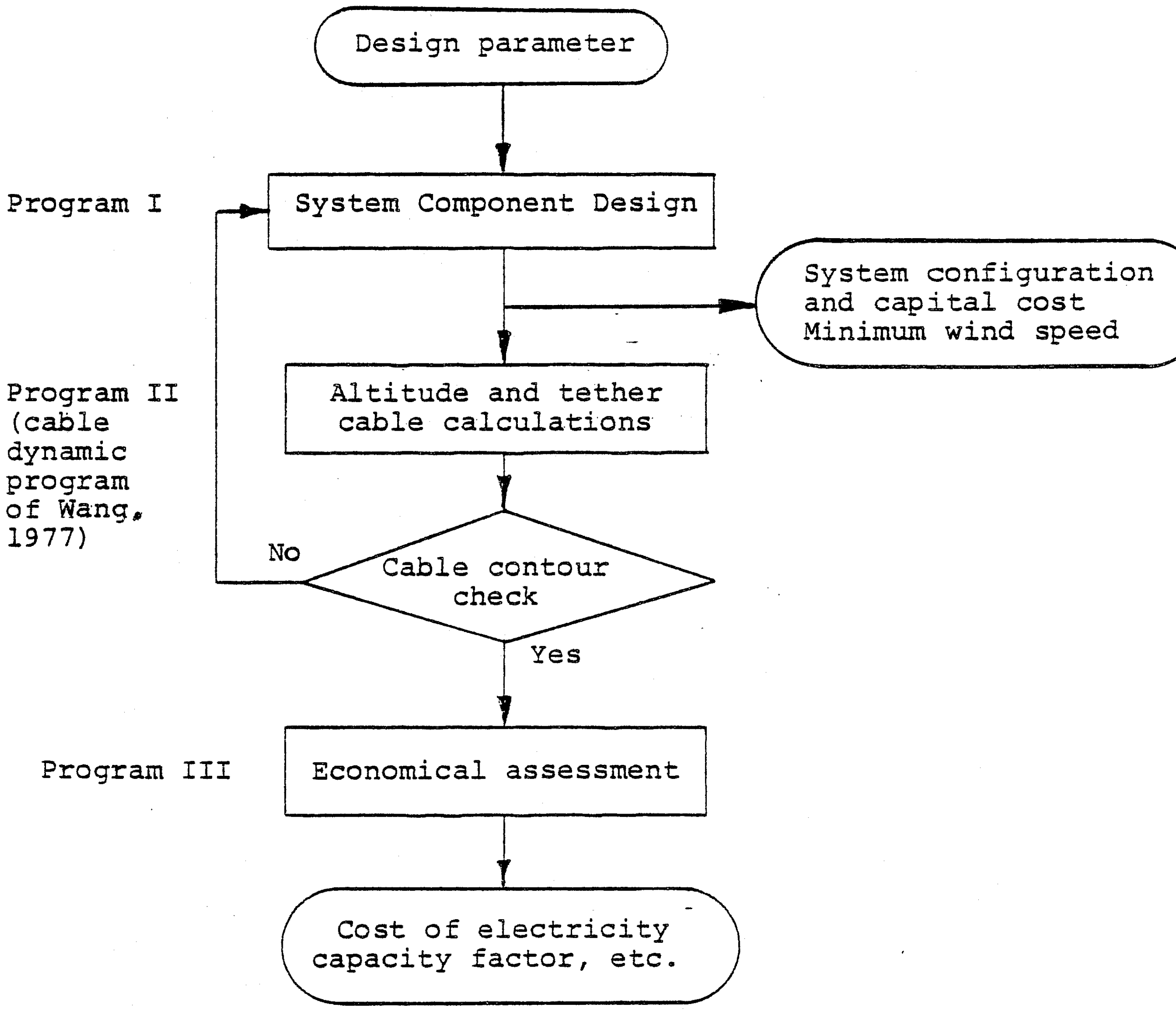


FIGURE 6.1 Flow chart of parametric design procedure

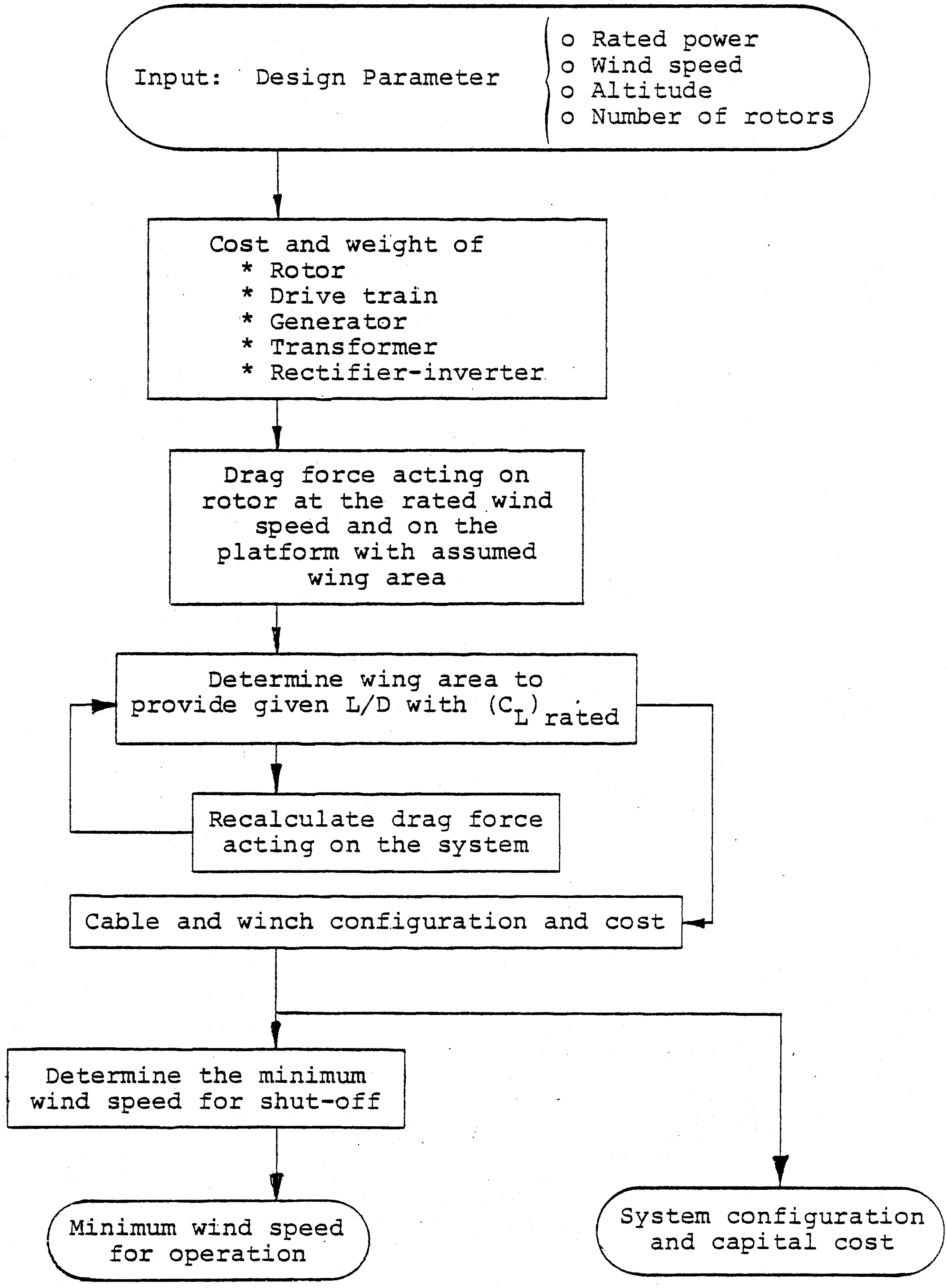


FIGURE 6.2 Flow chart of Program I

Once the correct wing area was obtained, the configurations and costs of cable and winch were calculated, followed by calculating the configuration and capital cost of the system. Then the wind speed was gradually reduced with a new lift coefficient, i.e., $C_{L\ max}$ of 2 until L/D of the platform became unity. This wind speed is the cut-in speed on the low wind speed side for the TWES to stop generating the electricity.

6.2 PROGRAM II (CABLE DYNAMIC PROGRAM)

This computer program was developed by Wang (1977). The input to this program were the lifting force and drag force, at the platform, cable's dimensions and its mechanical properties, wind profile, and air density profile. The outputs of the program were the tension and the displacement of the cable for the given condition. For all cases we ran, the program showed that no critical cases were found in terms of the cable angle. Therefore, this program was later eliminated from the procedure.

6.3 PROGRAM III (ECONOMICAL ASSESSMENT PROGRAM)

The structure of the program is shown in Figure 6.3. The results of the system component design program were inputted to this program, as well as the typical efficiencies of the components described in the previous section. The wind environment was entered as Weibull distribution. The annual electrical output was calculated from the 9-month power production curve by the numerical integration. The cost of electricity (COE) produced by wind turbines was computed by using the formula described in the previous section. It must be mentioned that the loss of power output due to the 9-month operation and amount of pumpback power were taken into account in the above COE calculations.

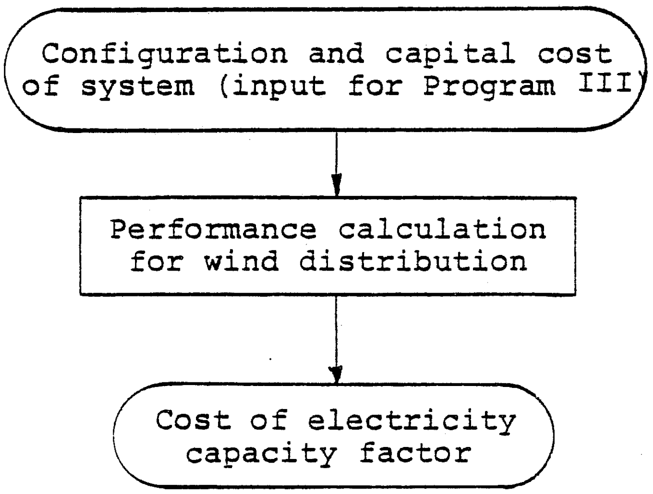


FIGURE 6.3 Flow chart for Program III

7.0 RESULT OF PARAMETRIC STUDY

The computer programs described in the previous section were used to optimize the Tethered Wind Energy System in terms of the cost of electricity for various parameters. These included the rated wind speed, rated altitude, rated power, and number of rotors. In this parametric study we specified the rated power, i.e., 500 kw, 1 MW or 2 MW and evaluated the effect of the parameters. During the course of economical assessment, we discovered that the cost of electricity with the hybrid concept was extremely high, i.e., by a factor of about 7. This was mainly attributable to the high cost of large-scale balloon construction. Due to this fact we have dropped the hybrid concept for the further study and all results presented hereafter are those for the VTOL concept.

7.1 PARAMETRIC STUDY

7.1.1 Rated Altitude

In order to design a TWES of a specified rated power, there exist an infinite number of choices regarding the altitude to be deployed. The effect of changing altitude was studied and the results for the 2 MW system are shown in Figure 7.1. It is seen that the minimum COE occurs at the 300 mb level, followed by the 400 mb level. It was expected to find the minimum COE at the 300 mb level, due to the highest annual wind density available at this altitude (see Figure 2.5(b)). However, it was rather surprising to find that the minimum COE at 400 mb is less than that at 200 mb. The sizes of the platforms were found to be similar, but the rated wind speeds which gave the minimum COE's differed about 10 m/sec between these two altitudes. The system with higher rated wind requires a stronger and longer cable. It means that a bigger and more sophisticated winching mechanism on the ground station is required. As will be seen later, the cost percentage

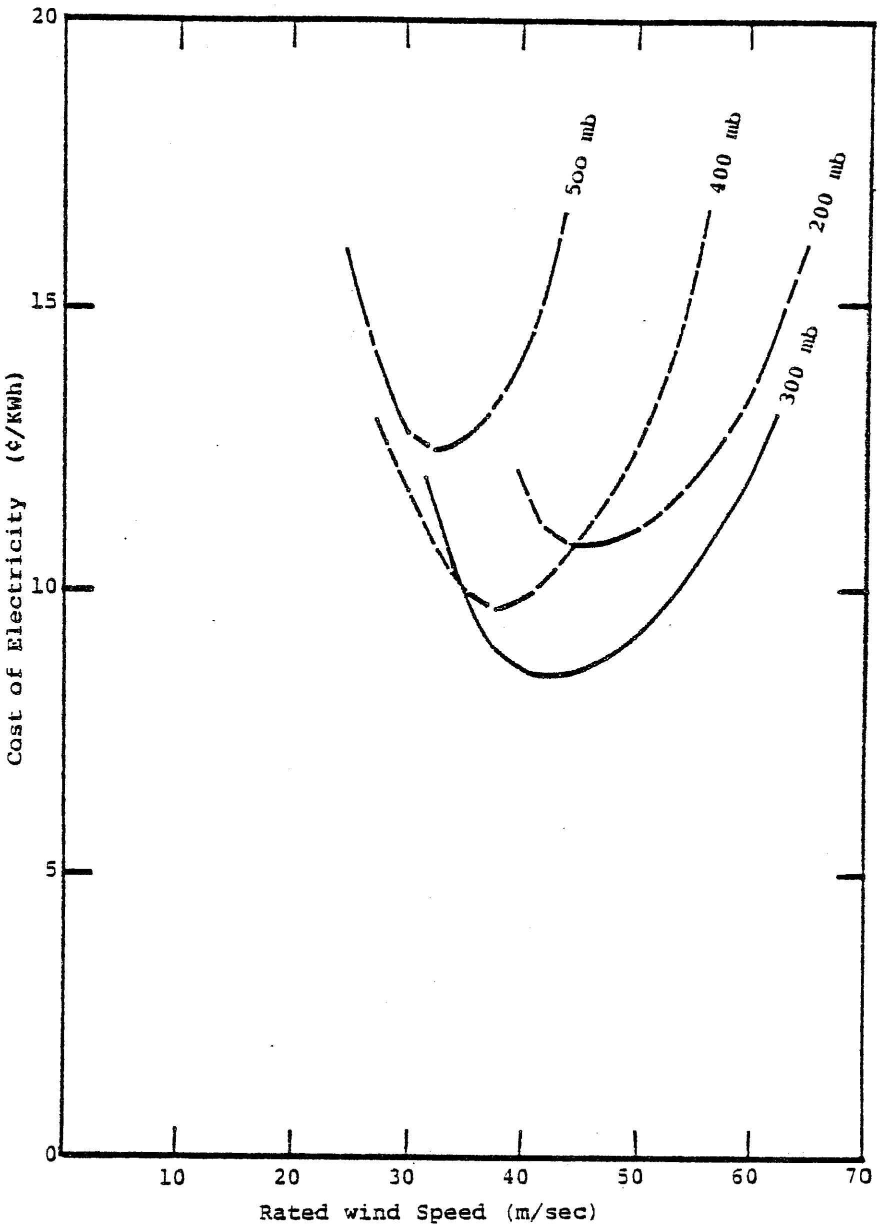


FIGURE 7.1 Cost of Electricity for 2MW TWES

of winch among the system cost is substantial (see Figure 7.6). A more expensive winch means a higher COE. It is for this reason that the COE at 200 mb is higher than that of 400 mb.

7.1.2 Rated Wind Speed

Figure 7.1 also shows the variation of COE with rated wind speed. The minimum COE points were found at 45 m/sec for 200 mb, 43 m/sec for 300 mb, 38 m/sec for 400 mb. For the ground wind power station, it is well known that the higher rated wind speed is not necessarily advantageous in terms of COE. This phenomena holds true even for the Tethered Wind Energy System.

7.1.3 Number of Rotors

The reduction of the capital cost was observed by reducing the number of rotors (Figure 7.2). The general trend here is that the larger the rated power, the cheaper the final COE. If we increase the number of rotors, the rated power of each subsystem attached to the rotor shaft decreases. The unit weight per unit power naturally increases for the smaller subsystem. This indicates that, for an efficient COE, the platform should carry as large subcomponents as possible. It should again be mentioned, however, that the light-weighted subcomponents available now are all limited to small power output, the maximum of 500 kw, so that an efficient design of TWES with large subcomponents, or equivalent large rated power, is not possible with the current state-of-the-art.

7.1.4 Rated Power

The effect of rated power specified on COE was studied and the results are shown in Figure 7.3. All of the components except for the rotor reduced in the cost/unit weight or equivalent weight/unit power. However, the practical limit exists in the size system which can be built without developing new sub-

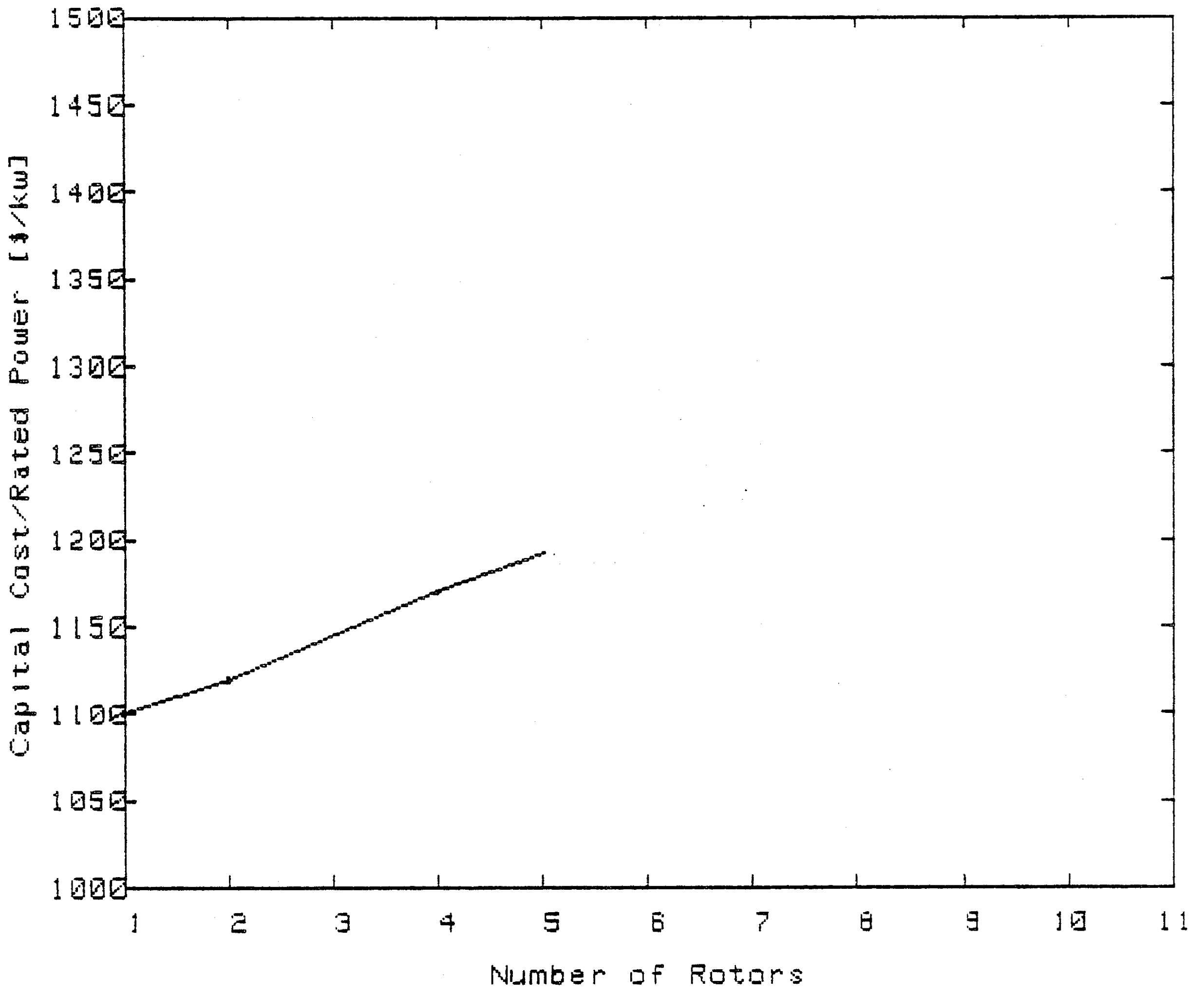


FIGURE 7.2 Capital cost/Rated power vs. Number of rotors

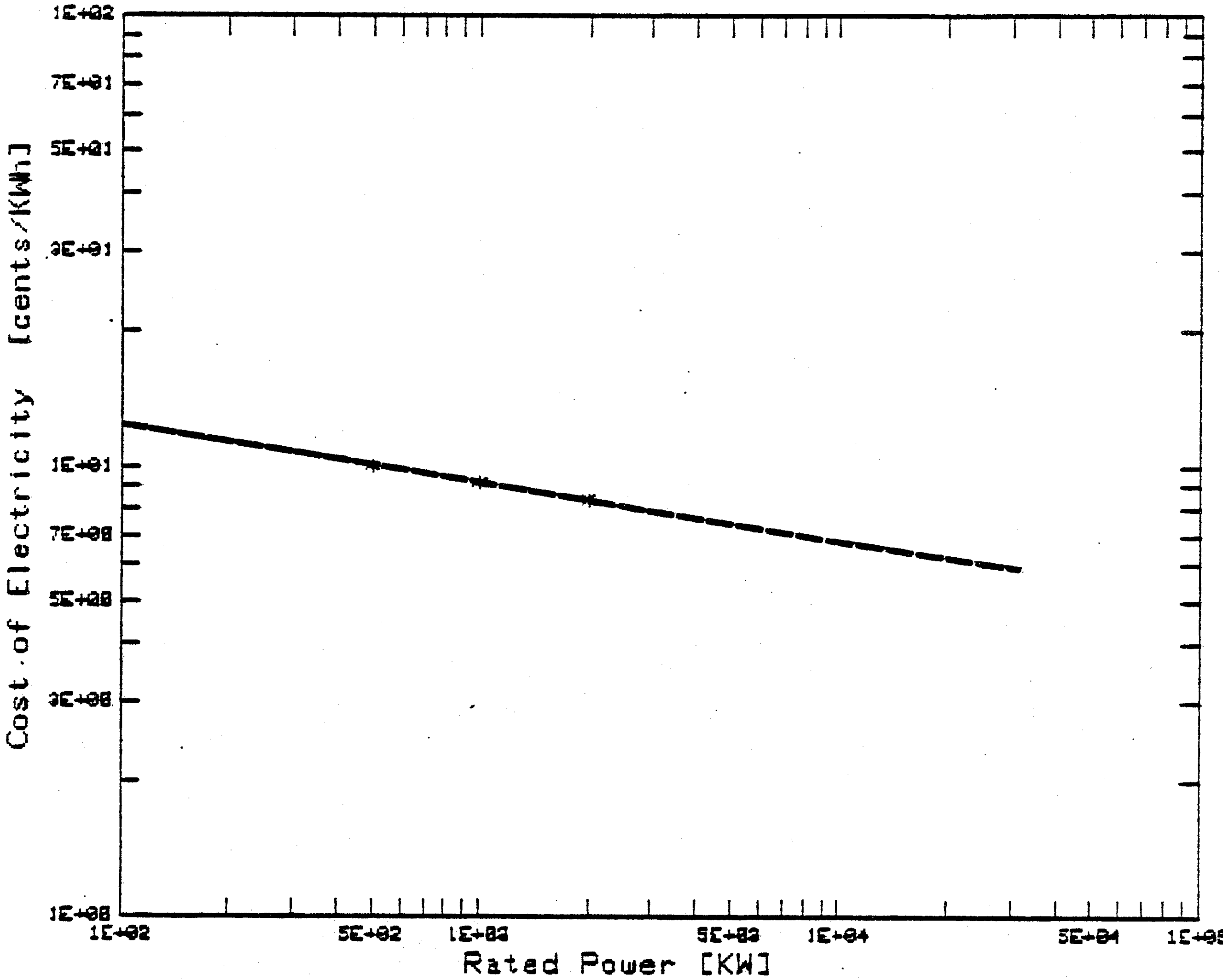


FIGURE 7.3 Cost of Electricity as a function of Rated Power

components, as has been mentioned before. Nevertheless, the extrapolation from 500 kw, 1 MW and 2 MW in Figure 7.3 shows potential hope for very competitive COE with the higher rated system, such as 20 MW, or higher.

7.2 OPTIMUM DESIGN FOR 2 MW

As has been seen from Figure 7.1, the optimum design point for 2 MW power station is at the altitude of 300 mb and rated wind speed of 43 meters (see Table 7.1 for summary of the optimum design). The cost of electricity obtained here is 8.4¢/kwh. The system does not have the conventional cut-off wind speed with an altitude maneuvering method employed. In case of high wind condition, the platform will reduce the lift force by controlling the flaps in order to search for an altitude having the rated wind speed. Cut-in wind speed was determined based on the station-keeping availability of the system as has been mentioned earlier. The cut-in speed for the optimum system is 27 m/sec, below which the rotors should be rotated to act as vertical thrusters. The power duration curve of the optimum system is shown in Figure 7.4. The capacity factor of .43 was found by integrating the power duration curve.

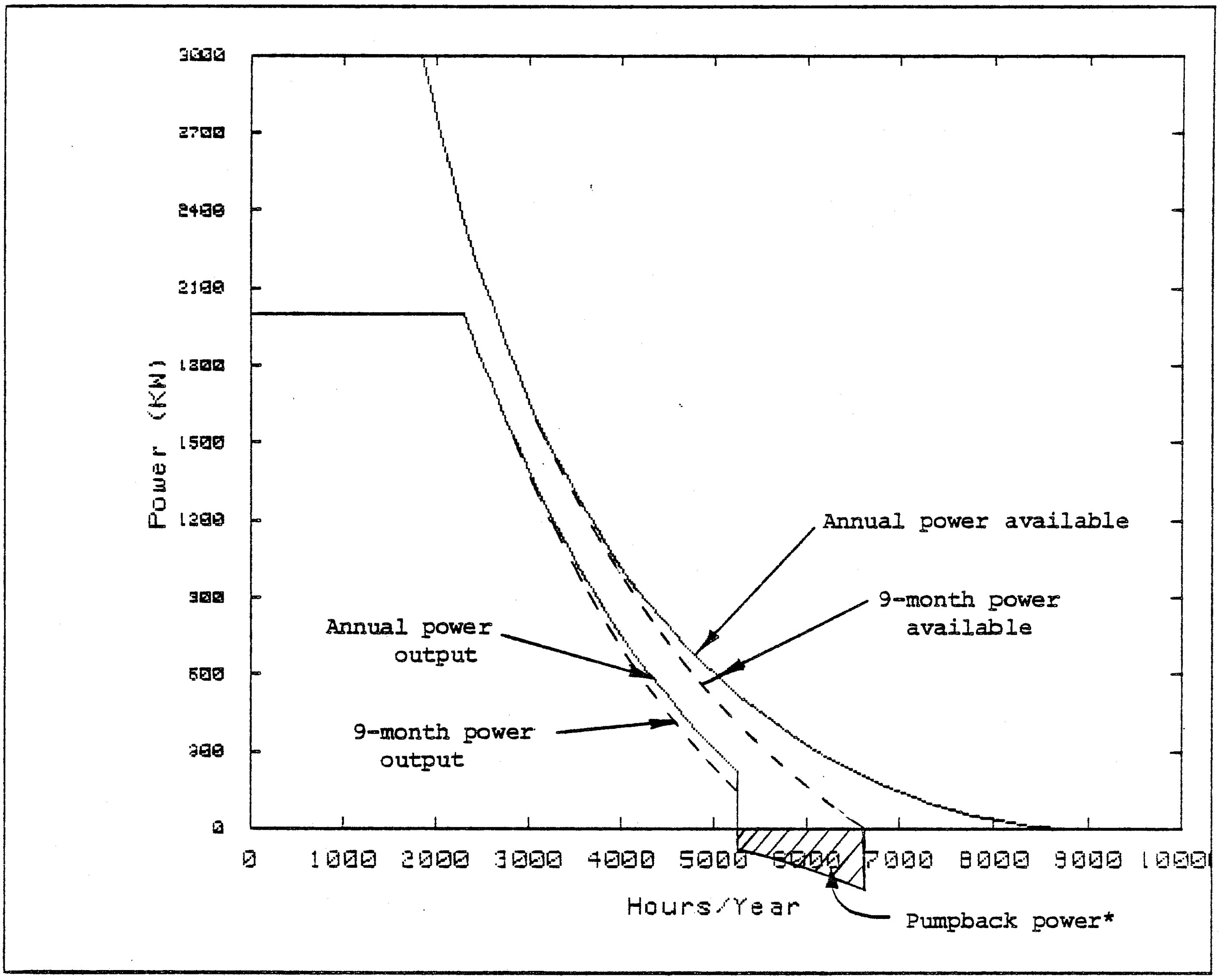
Figure 7.5 shows the calculated result of the cable profile shape for the optimum design. At the rated wind speed, the tension of the cable is 18,000 kg (= 176526N). The tension is substantially large compared to the aerodynamic force on the cable so that the slack of the cable is almost negligible. This fact proves the assumption made for the cable dynamic calculations as has been mentioned before. However, at the cut-in wind speed, the lift and drag of the platform reduces so that the tension applied at the platform is not quite as large as at the rated condition. Therefore, the effect of the cable weight becomes visible, as shown in Figure 7.5. However, the aerodynamic forces on the cable were not significant enough for either case to cause altitude loss or serious safety problems near the ground (the cable angle is 28° for this worst case).

TABLE 7.1

SUMMARY OF OPTIMUM DESIGN 2 MW TWES

Rated power	2 MW
Rated altitude	9160 m (300 mb)
Rated wind speed	43 m/sec
Cut-in wind speed	27 m/sec
Number of rotors	4
Rotor diameter	6.4 m
Weight of generating system	7,575 kg
Total airborne weight	13,500 kg
Wing area*	606 m^2
Aspect ratio of wing	10
L/D at rated condition	1
Tether cross-sectional area	121.39 mm^2
Maximum allowable tension on tether	18,000 kg
Length of tether	13.74 km
Cross-sectional area of kevlar	96.27 mm^2
Cross-sectional area of aluminum	25.12 mm^2
Total cable weight	2,850 kg
Capital cost	$2,340K
Capacity factor	.43
Cost of electricity	8.4¢/kwh

Note * The tailplane size was not determined here since it was not considered to be essential for the present study.



* (Estimated approximately 5% from Fletcher and Sapuppo, 1981)

FIGURE 7.4 Power duration curve for optimum design 2 MW TWES

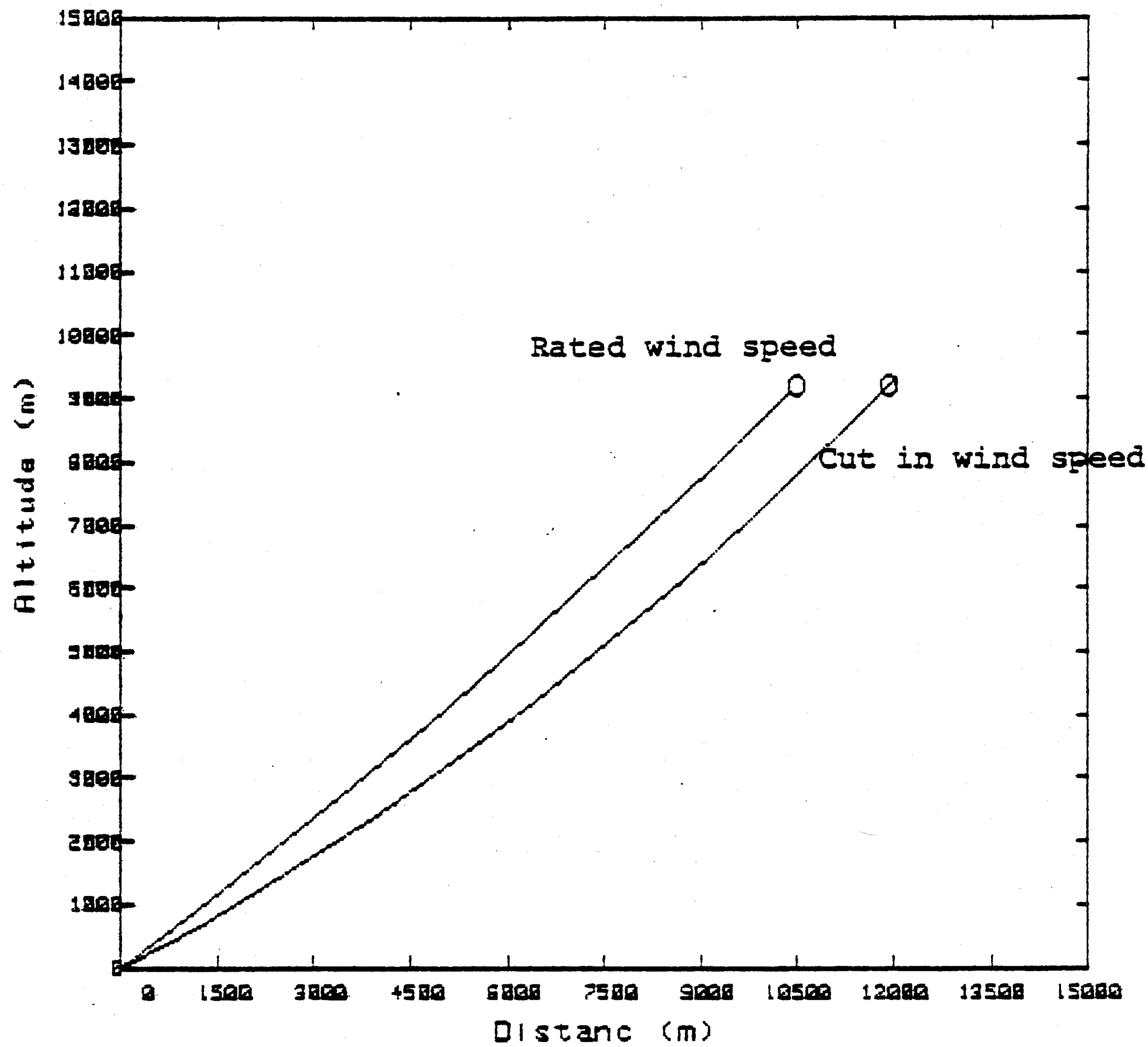
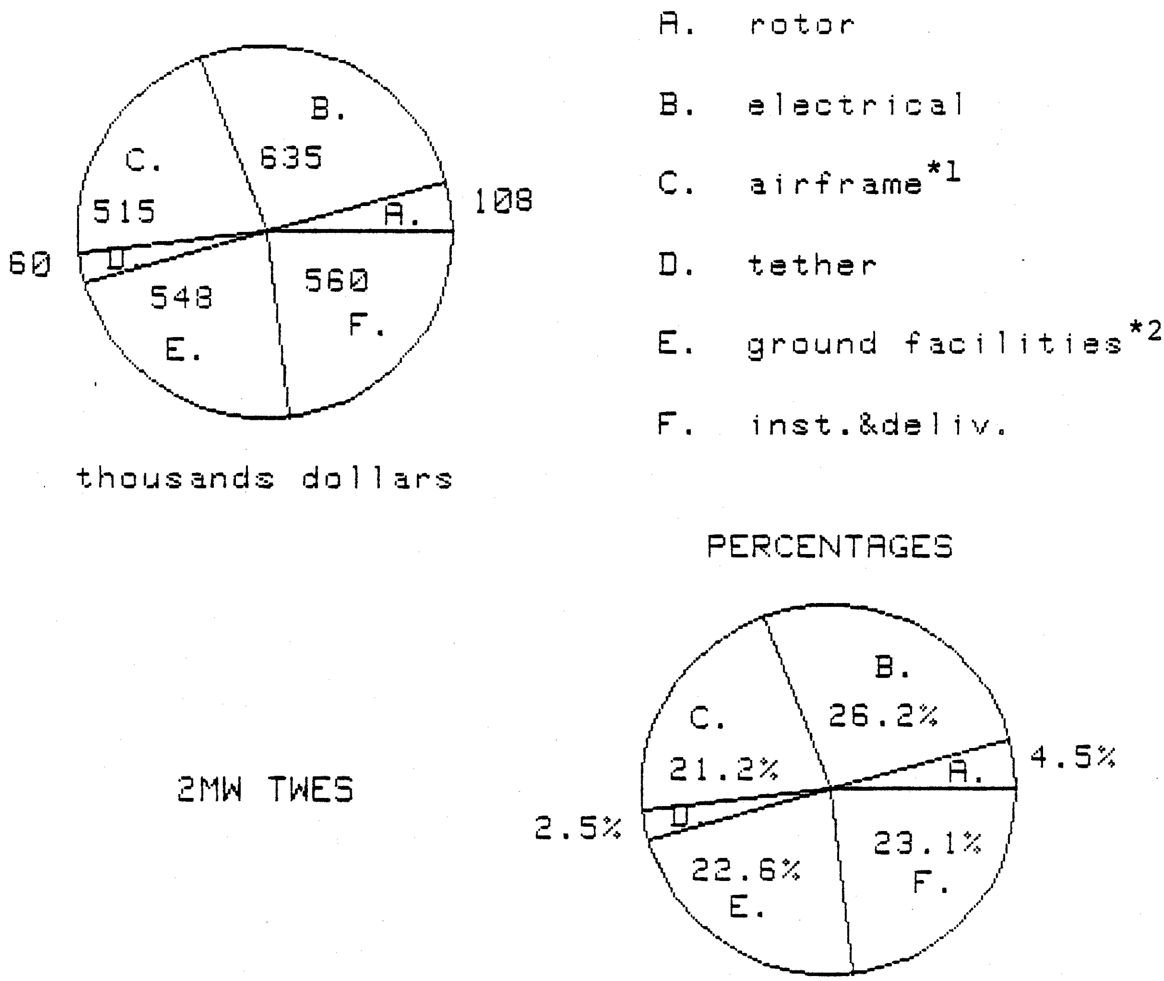


FIGURE 7.5 Behavior of tether for the optimum design 2MW TWES

The cost breakdown and weight distribution of the optimum design of 2 MW TWES are shown in Figures 7.6 and 7.7, respectively. It is seen that the costs of the electrical subsystem, airframe, ground facilities (winch) and installation are the major portions. The largest cost among all is from the generating subsystem (rotor/gear/generator/transformer/rectifier/inverter). Therefore, the largest cost reduction of the system can be expected, if the electrical subsystem of large power can be manufactured economically. The winch to which the cost is referred here is that of the underwater towing system. Such a system is expensive due to the adverse environment in which the system is used. The TWES deployment winch will not require consideration for sea environment, and thus should be designed and manufactured less expensively. Such development would also reduce the cost of electricity substantially.

As is seen from Figure 7.7, the transmission and airframe consist of 80% of the platform weight. This fact is inherent in the TWES and will not change much even with the advent of new technology in the future regarding gears and airframe materials.



<u>Note</u>

*1 The shrouds are included in C (airframe)

*2 The winch system is included in E (ground facilities)

FIGURE 7.6 Capital cost breakdown of optimum design 2 MW TWES

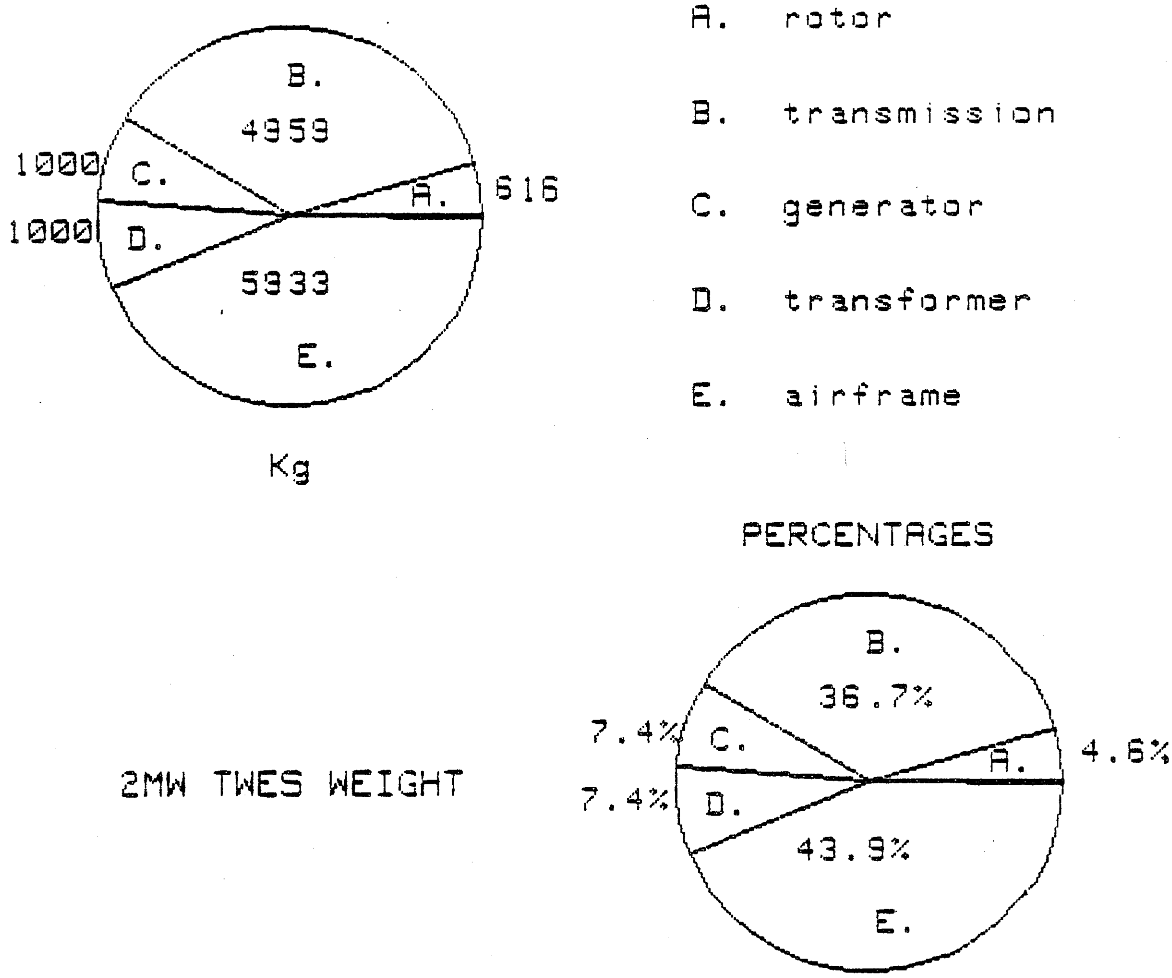


FIGURE 7.7 Weight breakdown of the optimum design 2 MW TWES platform

8.0 CONCLUSIONS AND RECOMMENDATIONS

The feasibility and economy of the Tethered Wind Energy System, if it is deployed in the U.S. sites, were studied. With the current state-of-the-art, it was determined that the TWES could be designed and built only up to the rated power of 2 MW. Unlike the ground level wind power station, the most critical aspect of the design work lies in the weight consideration. Existing aircraft technologies for various components of TWES were employed due to the similarity in their operational environments. However, the limitation of the maximum power existed in such technology, since the aircraft components do not usually require the power of larger than 500 KW. It was considered possible to have four 500 KW-rotor/generator configurations for the 2 MW station. Beyond 2 MW, a new development of subsystems particularly tailored toward the TWES environment will be required. It was for this reason that we here made a technical and economical assessment of TWES having the rated power of 500 KW, 1 MW and 2 MW only.

Two new lift generation concepts, i.e., hybrid and VTOL, were used here. These two new concepts have a great advantage over the wing concept of Australia or the balloon concept of Austria in that they do not require complicated operational and design features both at stall wind speeds and deployment/landing operations. Furthermore, they take full advantage of the high wind speeds at high altitude to generate enough lifting forces with wings. Since the cost of electricity with the hybrid lifting system was found to be larger than that with VTOL by a factor of about 7, the former concept was dropped from the further detailed studies.

The cost of electricity (COE) was calculated for various parameters on the basis of the available data for each component with the VTOL concept. When we chose the site for TWES at New York, New York, it was found that the optimum

2 MW system had the COE of 8.4¢/kwh. The rated wind speed for the optimum design was 43 m/sec and the operation altitude was at 300 mb (= 9160 m).

The capacity factor for the optimum design point was 43%. This cost of electricity is comparable to that of 2.5 MW MOD-2, a ground level wind power system, i.e., 10¢ at the site having the mean wind speed of 5.3 m/sec and 7¢ for 6.6 m/sec.

As has been seen from Figure 7.3, there is a natural trend of decrease in cost of electricity with the increase in the rated power of the platform. Although it is not realistic to extend the curve of Figure 7.3 into the higher rated power range, due to the lack of large power components, there exists a great potential to reduce the cost of electricity of TWES to a much lower level. As a matter of fact, it is our conclusion that the TWES, to be competitive in economy to other energy systems, must have the rated power of 10 MW or higher.

In order to prove the validity of such a discussion, however, a study for developing and designing large-scale aircraft types of components (larger than 500 KW) will be required. The components to be newly developed will include generators, transformers, rectifiers, inverters and tether cables. After such a developmental investigation is completed, the cost of electricity for TWES having the rated power of larger than 10 MW will be more accurately assessed. It is, therefore, recommended that such a developmental study, followed by the assessment of COE for TWES of 10 MW or larger, is to be conducted to determine the fate of the Tethered Wind Energy System as the future energy generating system in the United States.

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15. Supplementary Notes

16. Abstract (Limit: 200 words)

The objective of this report was to establish the potential of tethered wind energy systems for energy conversion in the upper atmosphere. Of the concepts investigated, the VTOL lift generation concept had the highest potential.

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b. Identifiers/Open-Ended Terms Tethered Wind Energy Systems ; TWES

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